VOL. 254 JULY 1956 No. 7

American Journal of Science

Established in 1818 by Benjamin Silliman

EDITORS
JOHN RODGERS—JOSEPH T. GREGORY

ASSOCIATE EDITORS

REGINALD A. DALY, CAMBRIDGE, MASS.
A. F. BUDDINGTON, PRINCETON, N. J.
CARL O. DUNBAR
MATT WALTON
HENRY MARGENAU
RICHARD F. FLINT
HORACE WINCHELL
HAROLD G. CASSIDY
EDWARD S. DEEVEY, JR.
G. EVELYN HUTCHINSON, NEW HAVEN, CONN.
LEASON H. ADAMS
WILMOT H. BRADLEY, WASHINGTON, D. C.
WILLIAM H. TWENHOFEL, ORLANDO, FLORIDA
HOWEL WILLIAMS, BERKELEY, CALIF.
FREDERICK J. ALCOCK, OTTAWA, CANADA
CECIL E. TILLEY, CAMBRIDGE, ENGLAND
C. R. LONGWELL, PALO ALTO, CALIF.
ADOLPH KNOPF, STANFORD, CALIF.
GEORGE GAYLORD SIMPSON, NEW YORK, N. Y.

STERLING TOWER
YALE UNIVERSITY
NEW HAVEN, CONNECTICUT

Published monthly. Ten dollars a year. One dollar a copy.
Foreign, ten dollars sixty cents Canada, ten dollars thirty-five cents.

AMERICAN JOURNAL OF SCIENCE

Established in 1818 by Benjamin Silliman

THE FIRST SCIENTIFIC JOURNAL IN THE UNITED STATES

DEVOTED TO THE GEOLOGICAL SCIENCES AND TO RELATED FIELDS

Editors: JOHN RODGERS—JOSEPH T. GREGORY

Managing Editor: ELIZABETH G. WEINMAN

Entered as second-class matter at the Post Office at New Haven, Conn., under the Act of March 3, 1879. Published monthly at Sterling Tower, Yale University, New Haven, Conn.

Subscription rate $10 per year ($1.00 a number). Student rate $5 per year (application blanks available on request). Postage prepaid to the United States; 35 cents per year to Canada; 60 cents per year elsewhere.

The JOURNAL completed its *first* series of 50 volumes in 1845, its *second* series of 50 volumes in 1870, its *third* series of 50 volumes in 1895, its *fourth* series of 50 volumes in 1920, its *fifth* series of 36 volumes in 1938. Since 1938 the numbering by series has been discontinued, and volumes are annual and bear the whole numbers as of 1818, that for 1939 being volume 237.

Back numbers and volumes, also cumulative indices of all series, may with few exceptions be obtained from the office of the AMERICAN JOURNAL OF SCIENCE, Sterling Tower, New Haven, Conn. Positive microfilm copies of each complete volume may be purchased by subscribers to the paper edition from *University Microfilms*, 313 N. First St., Ann Arbor, Michigan. Regular subscribers may purchase each past year in microcard form, from *The Microcard Foundation*, Wesleyan University, Middletown, Connecticut

INSTRUCTIONS TO CONTRIBUTORS

Manuscripts of articles submitted should follow the recommendations in the pamphlet "Suggestions to Authors" (Lane, 1935) and should be preceded by brief abstracts. They should be checked with special care before being submitted, to avoid changes in proof other than printer's errors.

References to literature should be listed alphabetically by authors at the end of the article; all references should be complete. For articles in journals or other serial publications, the reference should give in order: Author's name, year of publication, full title; name of periodical or series, volume number, inclusive pages. For books or other unnumbered publications, it should give: Author's name, year of publication, full title; place of publication, publisher. This form follows the recommendations in the pamphlet "Abbreviations used in publications of the U. S. Geological Survey", which is also the standard used for abbreviating names of periodicals, etc. Citations within an article should be to author and year, with specific pages wherever appropriate.

Plates (photographs), *figures* (line drawings), and *footnotes* should each be numbered consecutively through each article, using arabic numerals. If two photographs form one plate, they are figures 1 and 2 of that plate.

Illustrations should be neat and legible and should include explanations of symbols used. Copy that cannot be reproduced cannot be accepted. Plates and figures should be capable of reduction to not more than 4 by 7 inches, all lettering being at least 1/16th inch high after reduction. When necessary, one large map or table can be accepted, if it will not exceed 7 inches in width after reduction. Line drawings should be in black India ink on white drawing board, tracing cloth, or coordinate paper printed in blue. Photographs should be positive glossy prints. Photostatic and typewritten material cannot be accepted as copy for illustrations.

Reprints. Thirty separate copies of each article will be furnished to the author free of cost and without previous notice from him; these will be without a cover. Additional copies will be furnished at cost, which will of course be greater if the article is accompanied by plates involving unusual expense. Copies will be furnished with a printed cover giving the title, author, volume, page, and year, when specially ordered.

REFERENCE

Lane, B. H., 1935, Suggestions to authors of papers submitted for publication by the United States Geological Survey: U. S. Geol. Survey, Washington, D. C. (For sale by Superintendent of Documents, Washington, D. C. 35c.)

[American Journal of Science, Vol. 254, July 1956, P. 393-403]

American Journal of Science

JULY 1956

THE METAMORPHIC HISTORY OF THE SPRUCE PINE DISTRICT*

J. LAURENCE KULP and ARIE POLDERVAART

ABSTRACT. The Spruce Pine District is located on the Blue Ridge Plateau in western North Carolina. The rocks of the area consist of mica and hornblende gneisses and schists, quartzofeldspathic gneisses, ultramafic rocks, pegmatite and alaskite, granite, metadiabase and metagabbro, and younger, unmetamorphosed diabase. Field relations indicate two distinct periods of regional metamorphism. The first was Precambrian and was attended by plastic deformation, producing the Cranberry-Henderson and the Carolina-Roan gneisses from the original sedimentary sequence. Ultramafics were intruded into the Carolina-Roan gneiss along the keel of the geosyncline during the early stages of this period of metamorphism. Small granite intrusions in the Cranberry gneiss may have resulted from mobilization of lower parts of the Cranberry rocks.

Apparently the first metamorphic phase was followed by a period of local crustal tension, during which the country rocks were essentially rigid. Local subsequent brecciation of the metamorphic rocks was followed by the emplacement of the Bakersville-Roan Mountain basaltic dike swarm with northeasterly trend. The second metamorphic cycle followed the emplacement of this basaltic magma. In the Bakersville-Roan Mountain area this cycle caused recrystallization of the diabase, gabbro, and the cementing material of the breccias to mineral assemblages of high metamorphic grade, but left the Cranberry gneiss virtually unaffected. Pegmatites and alaskites were intruded toward the end of this second cycle at 330 ± 10 million years ago.

Finally, there was another phase of crustal tension and diabase dike intrusion which may be Triassic.

INTRODUCTION

The Spruce Pine District has been studied and mapped on a scale of 1:125,000 by Keith (1903, 1905, 1907), but more recently general geologic mapping at scales of 1:12,000 and 1:24,000 has been carried on by the U. S. Geological Survey in cooperation with the North Carolina Department of Conservation and Development (Olsen, 1944; Parker, 1953; Brobst and Kulp, in press). This paper briefly reviews the geology of the district and attempts to synthesize the geologic history. Mafic intrusive rocks are the chief clues to the sequence of events in this complex metamorphic terrane. Field evidence indicates that the area has undergone two periods of regional metamorphism.

The area described in this paper occupies parts of Mitchell, Avery, and Yancey counties on the Blue Ridge plateau in western North Carolina, and a small part of eastern Tennessee along the northern slope of Roan Mountain. An index map (see fig. 1 of F. D. Eckelmann and Kulp, 1956) shows the regional setting of the Spruce Pine District.

The authors wish to acknowledge the helpful suggestions of W. H. Bucher, A. F. Buddington, H. H. Hess, D. A. Brobst, H. L. James, and W. S. White.

* Lamont Geological Observatory Contribution No. 141.

GENERAL GEOLOGY

Regional Setting

The Spruce Pine District lies west of the axis of the Appalachian geosyncline (King, 1950). The area (fig. 1) consists predominantly of intricately folded gneisses and schists. At the beginning of this century, Keith (1903, 1905, 1907) distinguished four main formations: the Carolina gneiss (mainly mica gneiss and schist), the Roan gneiss (mainly hornblende gneiss and schist), the Cranberry and Henderson granites (mainly quartzofeldspathic gneisses). More recent work by Brobst and Kulp (reports in press) has shown on structural, stratigraphic, and petrographic grounds that the Roan and Carolina are probably best considered facies of one formation, i.e., the Carolina-Roan. F. D. Eckelmann and Kulp (1956) have shown that the Cranberry and Henderson rocks are metasedimentary in origin and are stratigraphically equivalent. The Carolina-Roan formation and the underlying Cranberry-Henderson gneiss appear to represent an original sedimentary sequence, although some pyroclastic material may contribute to the Roan facies.

In the Spruce Pine District, these rocks form a broad synclinorium which plunges toward the southwest (fig. 1). Foliation and schistosity are parallel to the bedding planes of the original sediments. Garnet, kyanite, and staurolite have been found in the metamorphic rocks, but these minerals could not be used as indicators to map zones of different metamorphic grade. Numerous intrusive bodies of ultramafic rocks, pegmatite, alaskite, granite, and both metamorphosed and unmetamorphosed basaltic rocks penetrate the synclinorium.

Rock Types

Brief descriptions of the various rock types are given below, but more detailed descriptions will appear elsewhere (Brobst and Kulp, in press; F. D. Eckelmann and Kulp, 1956; Wilcox and Poldervaart, in preparation).

Cranberry-Henderson Gneiss.—Leucocratic, quartzofeldspathic gneisses of granitic composition with minor schists, consisting chiefly of quartz, microcline, plagioclase (albite-oligoclase), with little biotite, muscovite, epidote, and chlorite, accessory black opaque ore, apatite, sphene, calcite, allanite, and zircon, and occasional garnet and hornblende.

Carolina-Roan gneiss.—A. Roan facies. Various hornblende gneisses and schists of cafemic affinity, mainly composed of hornblende, actinolite, plagioclase (oligoclase-andesine), quartz, epidote, zoisite, biotite, garnet, diopside, and chlorite. Accessories include black opaque ore, sulphides, sphene, rutile, apatite, zircon, allanite, calcite, and sericite. Microcline may or may not be present. The schists are generally darker colored than the gneisses which contain more quartz and feldspar.

Layering is conspicuous throughout (pl. 3 of F. D. Eckelmann and Kulp, 1956) with dark schist bands alternating with paler-colored gneissose layers. The width of the layers is highly variable with a maximum of 3-4 feet and minimum measured in a few tenths of inches. The average thickness of individual bands is about 1 foot, and the schist bands appear to have approxi-

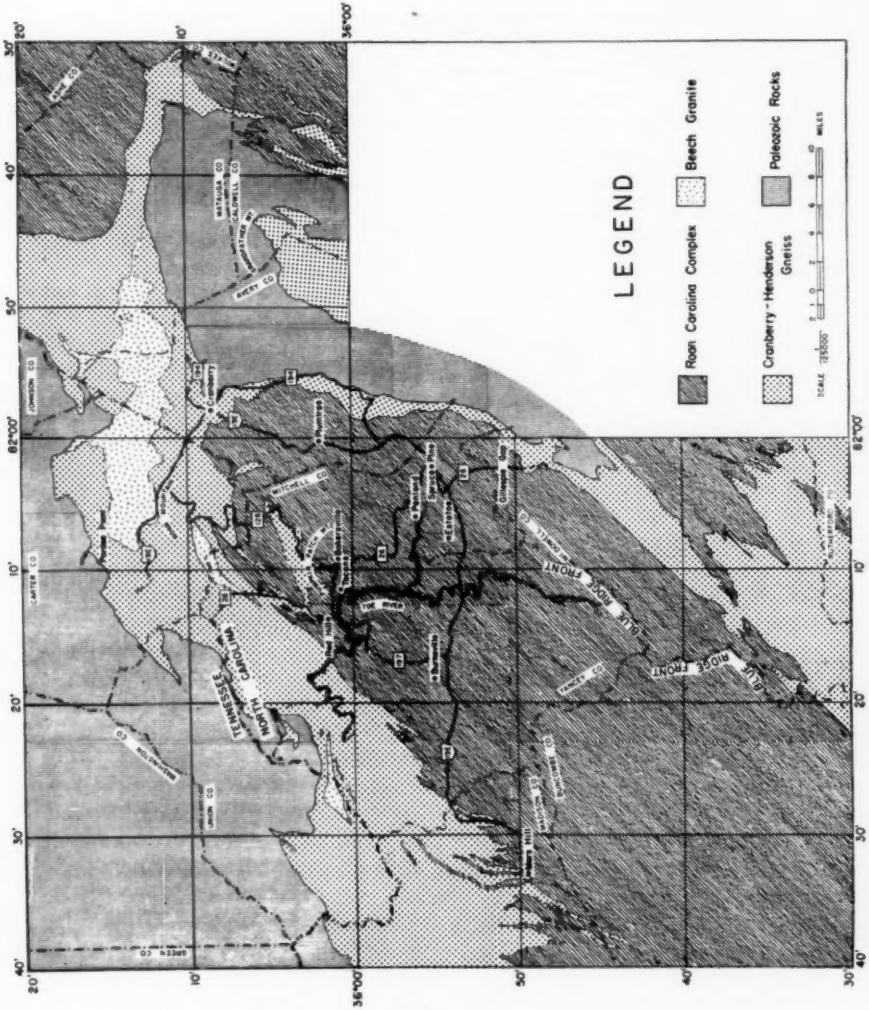


Fig. 1

mately the same width as the gneissose layers. The grain size is extremely variable, not only from one band to another but also within each layer.

B. Carolina facies. Various micaceous gneisses and schists of pelitic affinity consist of quartz, oligoclase, biotite, and muscovite. Accessory minerals are black opaque ore, epidote, apatite, allanite, zircon, sphene, rutile, chlorite, sulphides, and calcite. Chemical analyses show traces of carbon. Microcline may be absent or may occur in minor quantities in the schist, but is more prominent in the gneisses and may even exceed the amount of

oligoclase. The schists generally contain more muscovite than biotite, but in the gneisses this relationship is frequently reversed. With the appearance of hornblende and actinolite in increasing amounts, transitional phases between Carolina (mica gneisses and schists) and Roan (hornblende gneisses and schists) facies are produced. Garnet, kyanite, and staurolite may become prominent in certain layers, especially in the more schistose rocks. The Carolina facies is generally less well layered than the Roan facies. Alternating bands of mica schist and gneiss of varying width are found in places, but it is more usual to find one locality consisting predominantly of mica schists, while in another mica gneisses are more abundant.

Ultramafic rocks.—The ultramafic bodies consist of more or less altered dunite with olivine and disseminated chromite in minor amounts as the only primary minerals. Antigorite, enstatite, talc, anthophyllite, chlorite, serpentine, and magnetite may be found as secondary minerals. All transitions between slightly serpentinized dunite and soapstone bodies consisting largely of talc and serpentine are found.

Granite, pegmatite and alaskite.—The pegmatite and alaskite of the Spruce Pine District are closely allied; both are leucocratic, extremely variable in grain size, and the predominant alkali is sodium. The alaskite forms large unzoned bodies, has a granitic texture, and is coarse grained, but pegmatitic patches and schlieren are abundant. The pegmatites form smaller bodies some of which are zoned and of lenticular shape. The grain size is extremely variable but generally coarser than that of the alaskite, whereas the texture is pegmatitic. Both rock types consist mainly of oligoclase-albite, perthitic microcline, quartz and muscovite. Accessories are garnet, zoisite, biotite, zircon, apatite, columbite, uraninite, samarskite, beryl, tourmaline, black opaque ore, and sulphides.

Small patches of granite are found in the Cranberry in this area. This granite has the same mineral composition as the Cranberry rocks described above.

Metadiabase and metagabbro.—The rocks show textural and mineralogical variations which correspond to various phases in the recrystallization of basaltic to metabasaltic rocks (Poldervaart, 1953). Textures vary from subophitic to granoblastic. Palimpsest plagioclase and pyroxene may be heavily clouded and surrounded by newly formed metamorphic minerals including sodic plagioclase, green hornblende, almandine garnet, rhombic pyroxene, biotite, quartz, and black opaque ore. The minerals are typical of assemblages formed in the presence of low water concentrations. All the metabasaltic rocks are garnetiferous and the mineral assemblages are those of the amphibolite facies. Especially near the contacts, the rocks may show faintly to well developed foliation which usually parallels the contacts.

Diabase dikes.—Thin, unmetamorphosed diabase dikes occur in the area. These rocks consist of pagioclase (An_{50}), augite, and olivine which may be altered in part to serpentine. Textures are aphanitic to porphyritic and diabasic. Veins of calcite, zeolites and sulfides are associated with the dikes.

Geological Relationships

Cranberry and Carolina-Roan gneisses.—The Cranberry-Henderson gneiss is a typical metamorphic product of an arkosic series low in iron. The Carolina facies of the Carolina-Roan gneiss is the result of metamorphism of argillaceous sediments. The Roan rocks are probably the metamorphic equivalents of impure dolomitic limestones with intercalated arenaceous and argillaceous sediments. The intricate interlayering of the Roan and Carolina facies and the similar interlaying of the Roan-Carolina with the Cranberry-Henderson at their contact preclude an appreciable fraction of the Roan's having been volcanic flows. Further, the trace element composition of these rocks is not consistent with an origin from pure mafic volcanic materials (Brobst and Kulp, in press). The possibility that the Roan consists, at least in part, of intercalated reworked tuffs cannot be ruled out. An analogous unmetamorphosed sequence might be the tuff-sediment series in Puerto Rico.

The ultramafic rocks.—All of the dunite-peridotite bodies maintain the regional trend of the Alpine-type ultramafics of the Appalachians (Benson, 1926). Alteration of the dunite may be synchronous with its emplacement, or the result of subsequent regional metamorphism, or finally, due to emplacement of pegmatites which cut the ultramafic bodies. Alteration zones developed in the dunite adjacent to pegmatites have been described by Kulp and Brobst (1954).

In the Spruce Pine District, each ultramafic body shows a relatively unaltered dunite core surrounded by alteration zones of varying width. The contacts of these bodies with the country rocks may be conformable or cross-cutting, but the majority appear to be lenticular and to conform to the regional strike. It is believed that the ultramafics were emplaced during the initial stages of the regional metamorphism which produced the main plastic deformation of the Carolina-Roan rocks. During subsequent metamorphism and plastic deformation of the country rocks the intrusives were squeezed into new positions and probably both modified in shape and reduced in size, as has been observed in the Coast Ranges of California (Taliaferro, 1943). This process is thought to have been effected by marginal alteration of the dunite to various hydrous minerals with sheet structures, which effectively "greased" the contacts, while the dunite cores remained essentially unaltered (c.f., Turner and Verhoogen, 1951).

Granite, pegmatite and alaskite.—Small, irregular intrusions of granite are found in the Cranberry-Henderson unit. Contacts with country rocks are usually gradational, and it was at first believed that these slightly or non-foliated rocks were formed in situ by more thorough metamorphic recrystallization. Field evidence in this case is not determinative, and on the basis of field observations it could be argued with equal justification that the rocks were formed in place, or that they are igneous rocks with granitized marginal zones. However, the non-foliated granites contain sharply euhedral zircon crystals of characteristic habit, whereas the Cranberry-Henderson gneisses show only a few, well rounded zircons (F. D. Eckelmann and Kulp, 1956). This is regarded as evidence that the granites are true igneous rocks and

oligoclase. The schists generally contain more muscovite than biotite, but in the gneisses this relationship is frequently reversed. With the appearance of hornblende and actinolite in increasing amounts, transitional phases between Carolina (mica gneisses and schists) and Roan (hornblende gneisses and schists) facies are produced. Garnet, kyanite, and staurolite may become prominent in certain layers, especially in the more schistose rocks. The Carolina facies is generally less well layered than the Roan facies. Alternating bands of mica schist and gneiss of varying width are found in places, but it is more usual to find one locality consisting predominantly of mica schists, while in another mica gneisses are more abundant.

Ultramafic rocks.—The ultramafic bodies consist of more or less altered dunite with olivine and disseminated chromite in minor amounts as the only primary minerals. Antigorite, enstatite, talc, anthophyllite, chlorite, serpentine, and magnetite may be found as secondary minerals. All transitions between slightly serpentinized dunite and soapstone bodies consisting largely of talc and serpentine are found.

Granite, pegmatite and alaskite.—The pegmatite and alaskite of the Spruce Pine District are closely allied; both are leucocratic, extremely variable in grain size, and the predominant alkali is sodium. The alaskite forms large unzoned bodies, has a granitic texture, and is coarse grained, but pegmatitic patches and schlieren are abundant. The pegmatites form smaller bodies some of which are zoned and of lenticular shape. The grain size is extremely variable but generally coarser than that of the alaskite, whereas the texture is pegmatitic. Both rock types consist mainly of oligoclase-albite, perthitic microcline, quartz and muscovite. Accessories are garnet, zoisite, biotite, zircon, apatite, columbite, uraninite, samarskite, beryl, tourmaline, black opaque ore, and sulphides.

Small patches of granite are found in the Cranberry in this area. This granite has the same mineral composition as the Cranberry rocks described above.

Metadiabase and metagabbro.—The rocks show textural and mineralogical variations which correspond to various phases in the recrystallization of basaltic to metabasaltic rocks (Poldervaart, 1953). Textures vary from subophitic to granoblastic. Palimpsest plagioclase and pyroxene may be heavily clouded and surrounded by newly formed metamorphic minerals including sodic plagioclase, green hornblende, almandine garnet, rhombic pyroxene, biotite, quartz, and black opaque ore. The minerals are typical of assemblages formed in the presence of low water concentrations. All the metabasaltic rocks are garnetiferous and the mineral assemblages are those of the amphibolite facies. Especially near the contacts, the rocks may show faintly to well developed foliation which usually parallels the contacts.

Diabase dikes.—Thin, unmetamorphosed diabase dikes occur in the area. These rocks consist of pagioclase (An_{50}), augite, and olivine which may be altered in part to serpentine. Textures are aphanitic to porphyritic and diabasic. Veins of calcite, zeolites and sulfides are associated with the dikes.

Geological Relationships

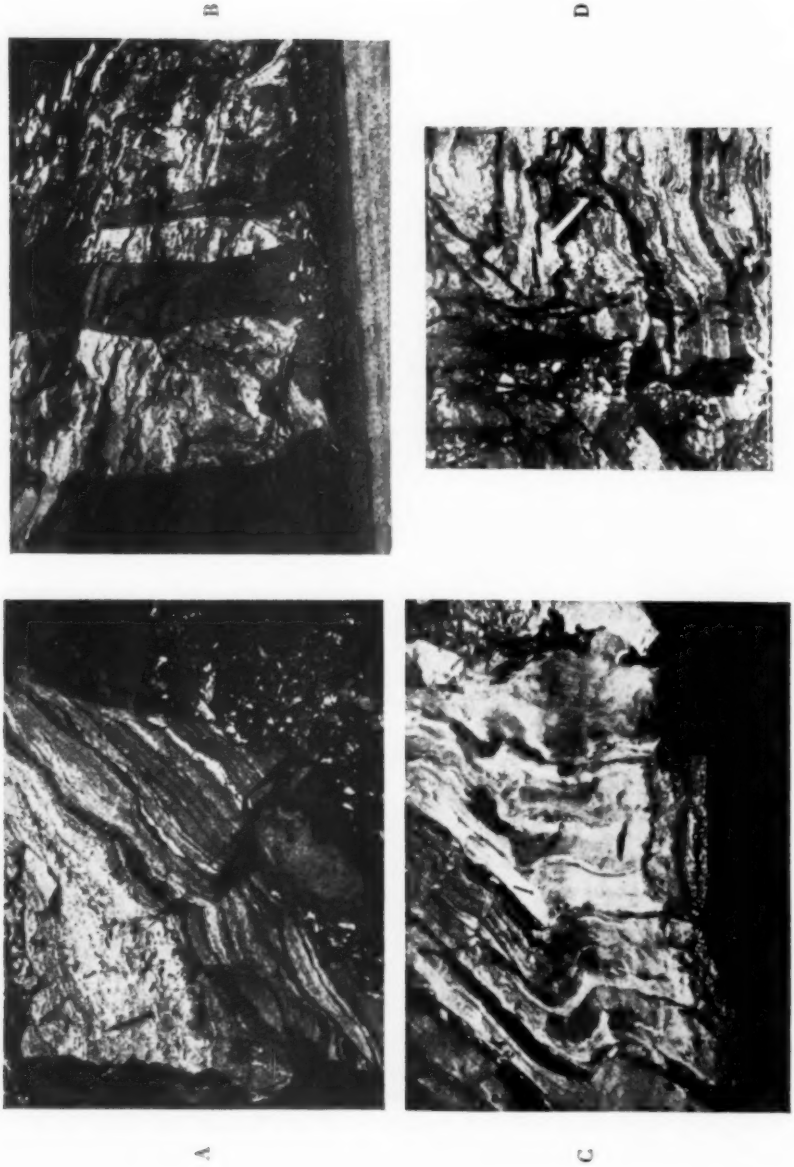
Cranberry and Carolina-Roan gneisses.—The Cranberry-Henderson gneiss is a typical metamorphic product of an arkosic series low in iron. The Carolina facies of the Carolina-Roan gneiss is the result of metamorphism of argillaceous sediments. The Roan rocks are probably the metamorphic equivalents of impure dolomitic limestones with intercalated arenaceous and argillaceous sediments. The intricate interlayering of the Roan and Carolina facies and the similar interlaying of the Roan-Carolina with the Cranberry-Henderson at their contact preclude an appreciable fraction of the Roan's having been volcanic flows. Further, the trace element composition of these rocks is not consistent with an origin from pure mafic volcanic materials (Brobst and Kulp, in press). The possibility that the Roan consists, at least in part, of intercalated reworked tuffs cannot be ruled out. An analogous unmetamorphosed sequence might be the tuff-sediment series in Puerto Rico.

The ultramafic rocks.—All of the dunite-peridotite bodies maintain the regional trend of the Alpine-type ultramafics of the Appalachians (Benson, 1926). Alteration of the dunite may be synchronous with its emplacement, or the result of subsequent regional metamorphism, or finally, due to emplacement of pegmatites which cut the ultramafic bodies. Alteration zones developed in the dunite adjacent to pegmatites have been described by Kulp and Brobst (1954).

In the Spruce Pine District, each ultramafic body shows a relatively unaltered dunite core surrounded by alteration zones of varying width. The contacts of these bodies with the country rocks may be conformable or cross-cutting, but the majority appear to be lenticular and to conform to the regional strike. It is believed that the ultramafics were emplaced during the initial stages of the regional metamorphism which produced the main plastic deformation of the Carolina-Roan rocks. During subsequent metamorphism and plastic deformation of the country rocks the intrusives were squeezed into new positions and probably both modified in shape and reduced in size, as has been observed in the Coast Ranges of California (Taliaferro, 1943). This process is thought to have been effected by marginal alteration of the dunite to various hydrous minerals with sheet structures, which effectively "greased" the contacts, while the dunite cores remained essentially unaltered (c.f., Turner and Verhoogen, 1951).

Granite, pegmatite and alaskite.—Small, irregular intrusions of granite are found in the Cranberry-Henderson unit. Contacts with country rocks are usually gradational, and it was at first believed that these slightly or non-foliated rocks were formed in situ by more thorough metamorphic recrystallization. Field evidence in this case is not determinative, and on the basis of field observations it could be argued with equal justification that the rocks were formed in place, or that they are igneous rocks with granitized marginal zones. However, the non-foliated granites contain sharply euhedral zircon crystals of characteristic habit, whereas the Cranberry-Henderson gneisses show only a few, well rounded zircons (F. D. Eckelmann and Kulp, 1956). This is regarded as evidence that the granites are true igneous rocks and

PLATE 1



were not formed in place (Poldervaart, 1950). They may not have traveled far and may still have been produced from fusion of the lower Cranberry-Henderson.

Pegmatite and alaskite of the Spruce Pine District are concentrated along the eastern and northeastern part of the synclinorium. They intrude the Carolina-Roan gneiss but do not appear to extend to the Cranberry-Henderson.

The pegmatite and alaskite are believed to have been emplaced during the later phases of the second regional metamorphism of the Carolina-Roan gneiss since there is no evidence of deformation or metamorphism of these rocks. Near the contacts, however, exposures may show faint to distinct foliation which parallels the foliation of the country rocks.

Metadiabase and metagabbro.—In the northwestern part of the area there are many parallel dikes of metadiabase, varying in width from 1/2 inch to 50 feet or more. The dikes cut across the foliation of the country rocks with sharp, clean contacts. Excellent exposures may be found along N. C. State Route 261 north from Bakersville and Tennessee State Route 143 on Roan Mountain. Here there are also local developments of breccia, in which angular fragments of foliated gneissic rocks are enveloped by a dark matrix which itself has been metamorphosed during the second metamorphic cycle (pl. 1-A).

Metagabbro of variable grain size is found as a large composite mass at Pumpkin Patch Mountain, northwest of Bakersville. Marginally the intrusive contains numerous inclusions of country rocks which have been mobilized in many cases by the gabbroic magma. Mobilization has resulted in modifications of the original outlines of the metasedimentary inclusions, and their foliation has been partly or wholly destroyed by thorough recrystallization. Xenoliths which have not been mobilized are angular to subangular in outline, and foliated in the same manner as the country rocks (pl. 2-A).

There can be no doubt that the basaltic rocks were emplaced after the first metamorphism of the Cranberry rocks, i.e., when these rocks were already tightly folded and plastically deformed. The local development of breccias, and the occurrence of the well defined dike swarm at Roan Mountain further indicates that the region was under tension. The fact that some of the Roan Mountain dikes are amygdaloidal is evidence that they were emplaced fairly near the surface and thus the environment was relatively cool. Finally, the fact that both basaltic rocks and breccias are themselves metamorphosed proves the existence of two distinct metamorphic cycles, separated by the intrusive phase of basaltic magma (pl. 1-B).

Two outcrops strongly suggest that the Bakersville gabbro was intruded into the Carolina-Roan prior to the final metamorphism which culminated in

---

A. Sharp contacts of layered granitized Cranberry in metadiabase matrix near top of Roan Mountain.

B. View from Roan Mountain road on Tennessee side showing three dikes cutting the foliation of the light-colored Cranberry rocks.

C. Excellent layering showing asymmetric folding along Crabtree Creek. Dark layers are hornblende gneiss, light layers are mica gneiss or schist.

D. Hammer point is at sharp contact of thin metadiabase dike and granitized Cranberry.

the pegmatite-alaskite invasion. One is along the Toe River on the West bank about 0.1 mile south of Toecane. Here a diabase-gabbro dike in the Carolina Roan has been metamorphosed to an amphibolite gneiss. The other is a sill of the porphyritic gabbro in the Carolina-Roan along the new roadcut on Route 197 two miles south of Red Hill. This sill has been completely recrystallized.

Shear zones.—A small number of major shear zones are found in the area. The most prominent of these dips at low angles and has a sinuous outcrop extending through Estato north to Penland and south toward the Gillespie Gap. This shear zone contains blocks of hydrothermally altered gneisses and schists, set in a matrix of schistose chlorite and actinolite with disseminated iron and copper sulphides. It is certain that those shear zones were initiated subsequent to the plastic deformation of the Carolina-Roan rocks and probably subsequent to pegmatite intrusion of the area. Mineralization and hydrothermal alteration occurred along these fracture zones apparently at relatively low temperature.

Diabase dikes.—A few thin dikes of unmetamorphosed diabase cut metasediments and pegmatites. Similar dikes occur throughout the Appalachians from Nova Scotia to Alabama. They are generally believed to be Triassic in age.

QUANTITATIVE AGE MEASUREMENTS

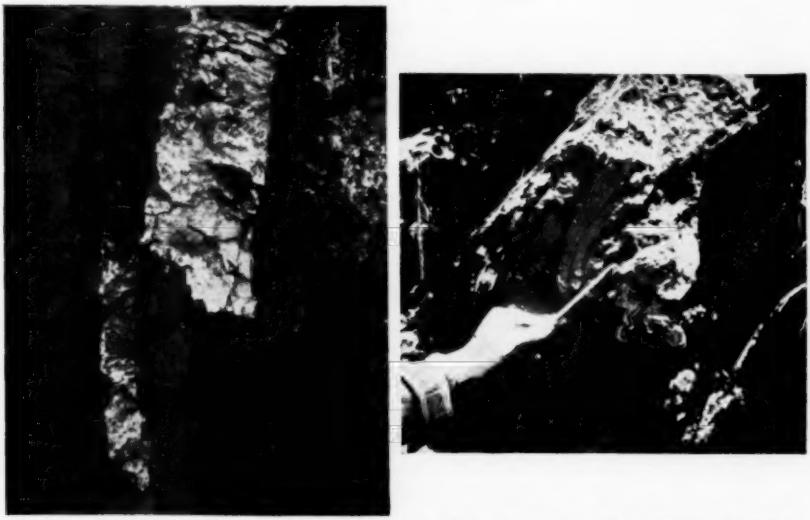
Recent complete isotopic and chemical studies on a number of radioactive minerals from the Spruce Pine pegmatites (W. R. Eckelmann and Kulp, 1956) show that these pegmatites, and therefore also the alaskite were emplaced 340 $\pm$ 20 million years ago. The completeness of this study and the concurrence of the ages obtained from the isotopic ratios makes the Spruce Pine District one of the well dated localities in North America. The earlier age estimates based only on chemical data range from 310-370 m.y. with exception of the Mars Hill monazite. This was shown to have been incorrectly dated at about 600 m.y. since it contains some common lead. When the proper common lead correction is made the age of the Mars Hill sample lies in the 300 m.y. age range also.

This date of 340 $\pm$ 20 m.y. indicates that the final major regional metamorphism climaxed at about the Ordovician-Silurian boundary. This may be correlated with the Taconic orogeny in New England. It is significant that stratigraphic evidence for the existence of a Taconian orogeny in the southern Appalachians has been accumulating rapidly for several years (Rodgers, 1952).

Recently Carr and Kulp (in press) have reported some potassium-argon ages for a number of Southern Appalachian localities. The inherent errors in this method are larger than in the uranium-lead method but do not exceed 20 percent. The perthite from Spruce Pine pegmatites indicates a date of origin around 300-350 m.y. ago consistent with the uranium-lead ages for these pegmatites. A sample of the Beech granite which is intrusive into the Cranberry gneiss just northwest of Roan Mountain and probably dates the culmination of the plastic deformation of the Cranberry-Henderson rocks

gave an apparent age of about 700 m.y. Cranberry and Carolina gneiss also gave ages in the same range. This proves that the first metamorphic cycle was Precambrian.

PLATE 2



A. Xenolith of Cranberry-Roan rock in metadiabase matrix on Roan Mountain road.
B. Typical folds found in the gneisses of the Spruce Pine District.

GEOLOGIC HISTORY

From the data given above the following geologic history can be constructed for the Spruce Pine District. The key position of the mafic intrusives in this interpretation will appear.

1. Deposition of a thick sedimentary sequence in the Appalachian geosyncline, now represented by the Carolina-Roan gneiss and the underlying Cranberry-Henderson gneiss. The Carolina facies becomes dominant over the Roan going up stratigraphically. This sedimentation occurred in the Precambrian (800-1000 m.y. ago) and possibly was contemporaneous with the deposition of the Talledega series in northern Alabama as suggested by King (1950).

2. Regional metamorphism occurred which plastically deformed the Cranberry-Henderson and Carolina-Roan gneisses. This probably occurred about 700 m.y. ago. Where the Cranberry rocks are in contact with lower Cambrian quartzites and phyllites such as around Grandfather Mountain and at Pardee Point there is an extreme contrast in degree of metamorphism. It is not certain, however, that this contact is a depositional one or is a thrust plane. Local pods of granite (Beech and Max Patch) were probably intruded into the Cranberry during the maximum of regional metamorphic cycle. Ultramafic bodies were emplaced during this first metamorphic cycle.

3. The first metamorphic cycle was succeeded by relative crustal tension during which the rocks were essentially rigid. Local brecciation of the metasedimentary rocks was followed by the intrusion of basaltic magma as a dike swarm with northeasterly trend in the Bakersville-Roan Mountain area. Some of these dikes extended south into the Carolina-Roan complex.

4. A second cycle of thermal metamorphism caused recrystallization of the basaltic rocks and the breccia matrix in the vicinity of Roan Mountain. The temperature was apparently greatest along the keel of the major syncline, causing local melting at depth with consequent pegmatite-alaskite intrusion into the Carolina-Roan rocks.

The ultramafic bodies which were intruded in the first regional metamorphism were altered peripherally and along joint planes. This second regional metamorphism ended at about the beginning of the Silurian (330 m.y. ago).

5. The development of shear zones after the region had cooled and was again under compression might reasonably be related to the Appalachian folding to the northwest at the end of the Paleozoic.

There is no certainty as to the age of the younger unmetamorphosed diabase dikes, but geomorphological evidence suggests that they are probably pre-Cretaceous, because younger sedimentary deposits are uninvaded. They are correlated tentatively with the Triassic intrusions found all along the eastern seaboard of North America.

GENERAL CONSIDERATIONS

The intense folding in the Cranberry-Henderson rocks which accompanied the first metamorphic cycle contrasts sharply with the lack of folding during the second. This may be related to the temperature and water distribution since even in regional metamorphism the surfaces of equal degree of metamorphism may dip rather steeply. Both cycles emphasize the complex problem of the spatial distribution of regional metamorphism. In the Spruce Pine District two distinct metamorphic periods can be recognized, and it is therefore of interest to inquire into the environmental conditions of these two cycles.

In the first metamorphic cycle a thick sequence of sediments was brought from its original state to one of essentially high-grade metamorphism, at least in the Cranberry and the Roan Mountain areas and presumably in the entire Blue Ridge of western North Carolina. During this process the rocks were tightly folded while in a plastic condition. The fold pattern of the area differs from place to place, and symmetrical folds are common in some localities, while others show highly asymmetrical folds which vary even from layer to layer (pl. 1-C and 2-B).

After cooling, tension, and intrusion of the gabbroic dikes, another thermal rise occurred which caused pegmatite formation in the vicinity of Spruce Pine-Plumtree-Bakersville but merely recrystallized the dikes on Roan Mountain. Along the Toe River at the two localities mentioned earlier, however, a gabbroic dike and sill may have been slightly deformed in addition to being thoroughly recrystallized.

On Roan Mountain the thinnest metadiabase dikes are perfectly clean-cut and undeformed (pl. 1-D). The dikes also cut sharply across the foliation of the country rocks (pl. 1-B), and there is no evidence of "streaming" of foliation planes in the immediate vicinity of the igneous contacts, as would be expected with continued folding. Therefore, it is concluded that the second cycle did not have the same high temperature or water content in the Roan Mountain area as the first cycle. The first cycle metamorphosed sedimentary rocks throughout the area but the second obviously affected only the unmetamorphosed basaltic rocks in the Roan Mountain area. However, both energy level and water concentrations at Roan Mountain were sufficiently high to effect metamorphic changes in the breccia matrix, diabase, and gabbro—rocks which had not been metamorphosed previously. The lack of plastic deformation in these rocks or the adjacent Cranberry gneiss may have been due only to low water concentration. With low water concentrations, rates of reaction would be much lower and the number of mineral transformations proceeding at any particular instant would be less, with the result that the rocks would remain essentially rigid at the prevailing temperatures and pressures.

References

Benson, W. N., 1926, Tectonic conditions accompanying the intrusion of basic and ultrabasic igneous rocks: Nat. Acad. Sci. Mem. 1, v. 19.

Brobst, D. A., and Kulp, J. L., Geology of the Spruce Pine District, North Carolina: U. S. Geol. Survey Prof. Paper, in press.

Carr, D R., and Kulp, J. L., Developments in potassium-argon dating: Geol. Soc. America Bull., in press.

Eckelmann, F. D., and Kulp, J. L., 1956, The sedimentary origin and stratigraphic equivalence of the so-called Cranberry and Henderson granites in western North Carolina: Am. Jour. Sci., v. 254, p. 288-315.

Eckelmann, W. R., and Kulp, J. L., 1956, The uranium-lead method of age determination II, North American localities: Geol. Soc. America Bull., in press.

Keith, Arthur, 1903, Description of the Cranberry quadrangle, North Carolina-Tennessee: U. S. Geol. Survey Geol. Atlas, folio 90.

———, 1905, Description of the Mount Mitchell quadrangle, North Carolina-Tennessee: U. S. Geol. Survey Geol. Atlas, folio 124.

———, 1907, Description of the Roan Mountain quadrangle, North Carolina-Tennessee: U. S. Geol. Survey Geol. Atlas, folio 151.

King, P. B., 1950, Tectonic framework of southeastern United States: Am. Assoc. Petroleum Geologists Bull., v. 34, p. 635-671.

Kulp, J. L., and Brobst, D. A., 1954, Notes on the dunite and the geochemistry of vermiculite at the Day Book dunite deposit, Yancey Country, North Carolina: Econ. Geology, v. 49, p. 211-220.

Olsen, J. C., 1944, Economic geology of the Spruce Pine pegmatite district, North Carolina: North Carolina Dept. Conserv. and Devel. Bull. 43, pt. 1.

Parker, J. M., 1953, Geology of part of the Spruce Pine District, North Carolina: North Carolina Dept. Conserv. and Devel. Bull. 65.

Poldervaart, Arie, 1950, Statistical studies of zircon as a criterion in granitization: Nature, v. 165, p. 574-575.

———, 1953, Metamorphism of basaltic rocks: a review: Geol. Soc. America Bull., v. 64, p. 259-273.

Rodgers, John, 1952, Absolute ages of radioactive minerals from the Appalachian region: Am. Jour. Sci., v. 250, p. 411-427.

Taliaferro, N. L., 1943, Franciscan-Knoxville problem: Am. Assoc. Petroleum Geologists Bull., v. 27, p. 109-219.

Turner, F. J., and Verhoogen, Jean, 1951, Igneous and metamorphic petrology: New York, McGraw-Hill Book Co.

Lamont Geological Observatory
Palisades, New York

[American Journal of Science, Vol. 254, July 1956, P. 404-412]

OCCURRENCE OF URANIUM IN SETH-LA-KAI DIATREME, HOPI BUTTES, ARIZONA

J. DAVID LOWELL

ABSTRACT. Uranium in the Seth-la-kai diatreme is concentrated in a thin volcanic sandstone bed and sparsely distributed through a travertine deposit. The uranium is thought to have been emplaced by hot spring activity near the close of the complex development of the diatreme structure in Pliocene time. Some of the structural features of the diatreme were reproduced using dynamic models.

INTRODUCTION

The Seth-la-kai uranium occurrence was investigated in August, 1954, to delineate the characteristics and paragenesis of the deposit. The Seth-la-kai structure was described by Hack (1942), as "Diatreme Number Four," because of indications that the vent was originally drilled by explosive volcanic activity. The area is on the Navajo Indian Reservation near Indian Wells trading post, 40 miles by road north of Holbrook, Arizona (fig. 1). It is in the south-central part of the Colorado Plateau and within the uranium metallogenic province of the Plateau.

The investigation consisted of geologic mapping and surface radiation mapping, part of which was done as a project for the United States Atomic Energy Commission, plus structural analysis using dynamic models, and limited petrographic work.

The writer is indebted to John W. Gruner, Charles A. Repenning, Eugene M. Shoemaker, and George A. Thompson, Jr. for many suggestions that are incorporated in this paper.

GEOLOGY

The area studied is in the Hopi Buttes volcanic field, Navajo County, Arizona, which is made up of over 200 volcanic centers (Hack, 1942) and has been dated by Lance (1954) as of Pliocene age. Many diatremes, volcanic necks, and lava domes occur in the vicinity of Indian Wells and, being resistant to erosion, crop out as mesas above the general valley level.

The volcanic rocks of the Hopi Buttes are grouped together to form the volcanic member of the Bidahochi formation (Repenning and Irwin, 1954) of Tertiary age. The Bidahochi formation in the region consists of a lacustrine lower member, a volcanic member, and a fluvial upper member. The Bidahochi in the Seth-la-kai area lies unconformably on the Wingate sandstone of Triassic age (Averitt, Detterman, Harshbarger, Repenning, and Wilson, 1955).

The general sequence of rock types in the Seth-la-kai diatreme ranges from dark-colored crumpled tuffs through calcareous tuffaceous beds to the cavernous travertine and irregularly bedded limestone that caps the structure.

Pyroclastic Unit "A" (figs. 1 and 2) is made up of poorly sorted tuff and agglomerate showing crude stratification, which may be in part due to selective fall-out of ejectamenta and in part due to incomplete reworking by fluvial processes. The unit has been penecontemporaneously crumpled into a series of blocks, overturned folds, and small thrust sheets. Pyroclastic Unit

"A" is continuous most of the way around the diatreme and is found in nearby erosional remnants. It averages 50 feet thick and overlies a surface of sharp relief cut into the lower member of the Bidahochi.

Pyroclastic Unit "A" is overlain by Pyroclastic Unit "B" at two points on the rim. Unit "B" is made up of intercalated tuff breccia and tuff to a maximum thickness of about 80 feet.

Where total thicknesses are exposed, Pyroclastic Unit "C" varies from 90 to 200 feet. It is a lenticular unit and probably exceeds 200 feet in thickness in the center of the structure. It is made up of approximately 60 percent travertine and tuffaceous lake deposits interbedded with 40 percent pyroclastic rocks ranging in size from fine-grained tuff to coarse tuff breccia. Individual beds within the unit can be traced from fine-grained tuff beds on the southwest edge to lapilli beds on the northwest; the particle size increased gradually from .5 mm to 5 mm in this distance. In a general way the tuff beds can be correlated with apparent remnants of a tuff breccia cinder cone near the outer, northeast edge of the diatreme (fig. 1, "East tuff breccia"). Also within Pyroclastic Unit "C", cavernous, irregularly bedded travertine grades laterally into thin, varve-like, calcareous beds containing an admixture of ash. The travertine beds probably represent deposition of a terrace of compact limestone, precipitated from hot spring waters due to the rapid release of pressure, and the varve-like beds were probably deposited in adjacent ponds where ash from the eruption of other volcanoes was accumulating. These calcareous units grade into pure tuff, presumably formed on the margins of the ponds or in the ponds at times of heavy ash falls.

Limburgite flow rocks crop out immediately north of the diatreme (fig. 2). The flows are normally black, whereas lavas that show evidence of violent eruption and grade into tuff breccia are more red in color (because of oxidation) and are vesicular. In general the lava flows show good columnar jointing but no flow banding.

The only fossil found was a local occurrence of algal limestone (Spongiostromata, probably *Cyanophyta*, personal communication, J. Harlan Johnson, 1955) near the top of Pyroclastic Unit "C". (In such an isolated pond probably no organisms other than algae would live in water that was carbonated and presumably quite hot.) One small occurrence of native sulfur was seen in Pyroclastic Unit "B", but the rocks in general show no alteration or staining by iron and sulfur compounds. These relations suggest that the quantity of H_2S was small in relation to CO_2. The abundance of travertine and the presence in it of an assemblage of rounded quartz with minor magnetite, mica and microcline grains (all indicative of mature detrital sediments) suggest that hot solutions charged with CO_2 may have dissolved $CaCO_3$ from underlying Triassic beds.

To all appearances the present structure of the Seth-la-kai diatreme was produced by collapse, caused by the removal of support underlying an area roughly centered about the point of intersection of the two cross sections shown on figure 1. The structure is roughly circular in plan view and is composed of inwardly dipping rocks. The steepest dips are along its northern and northeastern margins where down-faulting and drag have occurred against the

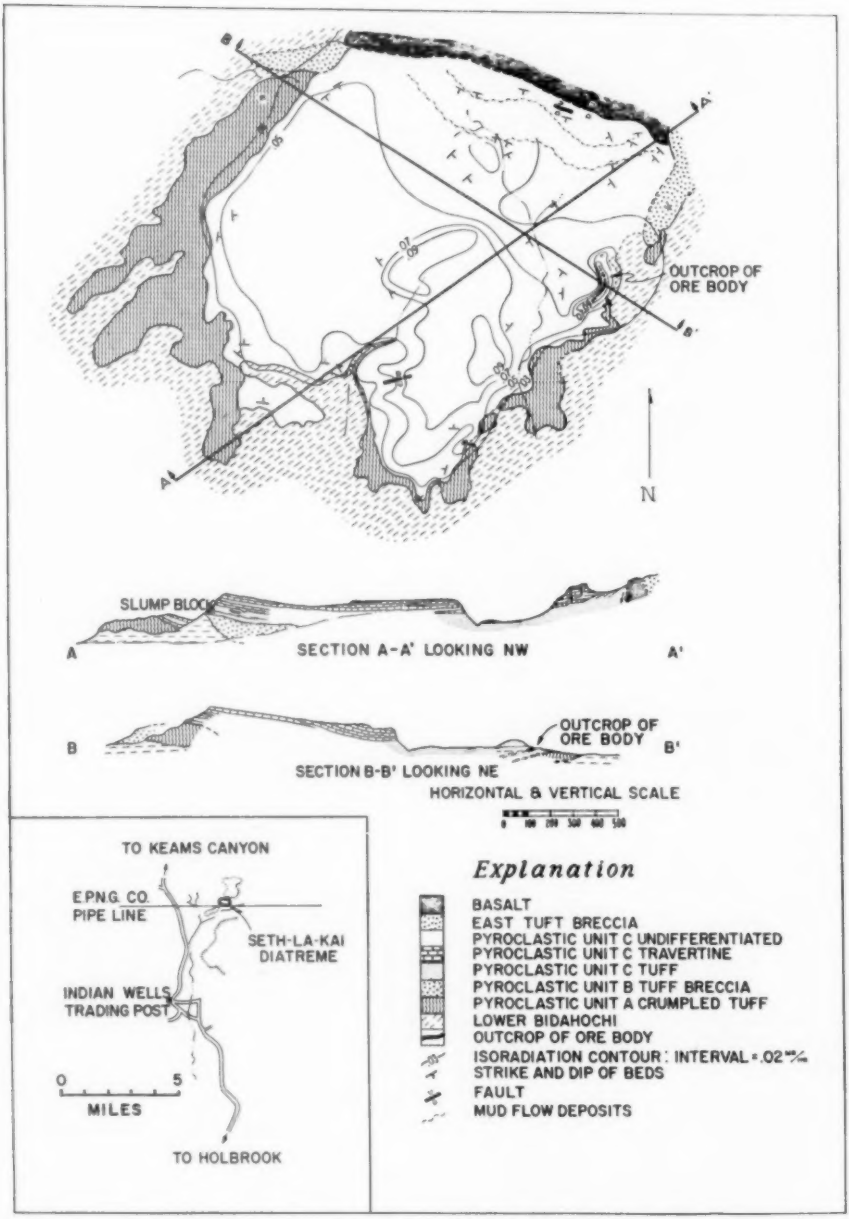


Fig. 1. Plan and sections of Seth-la-kai diatreme.

basalt-capped mesa to the north. The circular area in which rocks related to the diatreme are exposed is, therefore, slightly asymmetrical with respect to its center of collapse, which lies in its northeastern quadrant. Disproportionate erosion of the margin of the diatreme (fig. 2) adds somewhat to this asymmetry.

Topographically as well as structurally, the area of the center of collapse is the lowest part of the diatreme. This area is also characterized by many

Fig. 2. Oblique view of Seth-la-kai diatreme.

vertical pipes filled with unsorted and unstratified rock fragments and typically leading upwards into spring orifices marked by dome-shaped and cavernous calcareous tufa deposits. Dissection by erosion has left many of these pipes exposed in cross section on cliff faces. The center of collapse also is marked by numerous small faults within the pyroclastics and spring deposits. These faults are normally reverse faults and consistently have their downthrown side towards the center.

The surface of contact of the pyroclastic and calcareous deposits with the underlying crumpled beds and Bidahochi shales is visible on three sides of the diatreme and appears to be roughly funnel shaped. This funnel-shaped surface was probably formed either by explosive action at the onset of volcanic activity or by sliding and washing of Bidahochi shales and volcanic material into the diatreme vent at the conclusion of volcanic activity.

The formation of the diatreme probably occurred in several steps. It started with the drilling of the throat by an explosion so violent that the lower Bidahochi beds penetrated show only slight evidence of deformation; this deformation is at a point on the northeast edge of the structure. The eruption may have been phreatomagmatic, that is, caused by magma rising to a level of ground-water saturation where steam pressures were generated which blasted a vent to the surface. Presumably this, and possibly other eruptions, furnished the source rocks for Pyroclastic Unit "A". The material blown out was strewn over the area as a layer of heterogeneous pyroclastic debris. It was in places partly reworked by fluvial processes and shows crude stratification.

Hack (1942) has described Pyroclastic Unit "A" as being "pushed outward or contorted by later eruptions, or by compression caused by subsidence of the (diatreme) filling." Contortion of the unit is still intense however in an outlier 2000 feet south of the diatreme, so that subsidence in the diatreme is an unlikely cause. Explosion is also an unlikely cause, unless the throat was choked by fragments and covered by a cinder cone, so that the explosion was directed laterally to cause widespread crumpling in the adjacent pyroclastic material. An alternate explanation is that the crumpling is a drag phenomenon at the base of a widespread mud flow.

The deformation of Pyroclastic Unit "A" was followed by the deposition of tuff breccia (Pyroclastic Unit "B"). On the south side of the diatreme the tuff breccia forms a lenticular unit containing fragments of gray, argillaceous sandstone. On the northeast side it forms a short dike-like body, probably made up of debris from an explosion within the throat.

Volcanic ash from the eruption of other volcanoes collected within the depression to initiate the deposition of Unit "C". In some cases the ash is cemented by $CaCO_3$ which must have been derived from springs within the diatreme. Volcanic bombs from nearby diatremes are common. Mud flows containing large blocks of pyroclastic debris later spilled into the depression, possibly as outwash products of lava flows rising from a volcanic center immediately east of the diatreme. These mud flows contain many large boulders of basalt, of which some were planed flat by being dragged against the surface over which the flows moved, and others appear to have tumbled or to have

been blown into the diatreme depression. The mud flows occur only on the northeast side and are intricately interbedded with calcareous and tuffaceous deposits. The calcareous beds grade into travertine deposits and are interbedded with tuffs and rarely with lapilli beds.

Successive angular unconformities, apparently caused by repeated collapse of the diatreme contemporaneous with deposition within it, can be seen on the north side. In the final stage, when subsidence was almost complete and deposits were approaching the level of the surrounding area, deposition was restricted to travertine terraces and stream-worked pyroclastic material. Final subsidence produced broad sag structures and, on a small scale, many reverse faults, some of which were cemented by $CaCO_3$ from the hot springs.

During the deposition of Unit "C" recurrent activity in the volcanic center to the northeast resulted in emplacement of the "east tuff breccia" (fig. 1) and vesicular basalt which cut the earlier black lava flow just east of Seth-la-kai diatreme (fig. 1, section A-A′). Calcareous beds with inward dips were seen at one point and suggest that a diatreme developed there also but is now obscured by lava. The "east tuff breccia," which probably was derived from the volcanic center to the northeast, is thought to be equivalent to finer-grained tuff in the upper part of Unit "C".

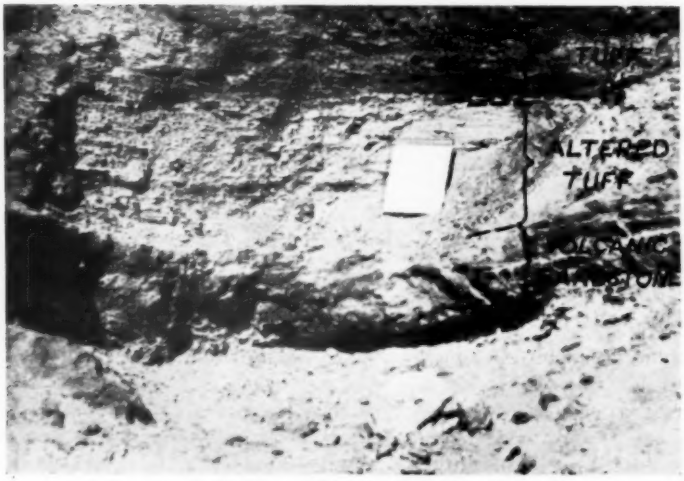
DESCRIPTION OF URANIUM MINERALIZATION

The Morale Claim ore body (fig. 1 and pl. 1-A) is localized by a coarse volcanic sandstone bed 6 to 18 inches thick. Uranium extends into tuff beds above and below the sandstone and the vertical limits of uranium mineralization roughly correspond to the limits of alteration in the tuff. In plate 1-A the altered tuff shows as light-colored material underlying dark, unaltered tuff. Petrographically the alteration appears to have been very weak, affecting lithic fragments less than 1 mm from completely fresh feldspar grains. Limonite, gypsum, psilomelane, montmorillonite, celedonite, and laumontite were identified as minerals probably formed by mineralizing solutions. Laumontite is included in the mineral assemblages of Zones I and II of the greenschist facies (Turner, 1934; Hutton and Turner, 1936) and is indicative of very low-grade metamorphism such as may have been effected by brief and low-temperature hydrothermal activity. The identity of the uranium mineral is not readily apparent either megascopically or petrographically. It is non-fluorescent, and possibly is included as submicroscopic grains in one of the other minerals. The ore where mined averaged approximately 0.20 percent U_3O_8 through a thickness of 2 feet. Mineralized rock can be traced laterally for 150 feet, but talus and mine waste cover the outcrop over much of this distance and prevented thorough sampling.

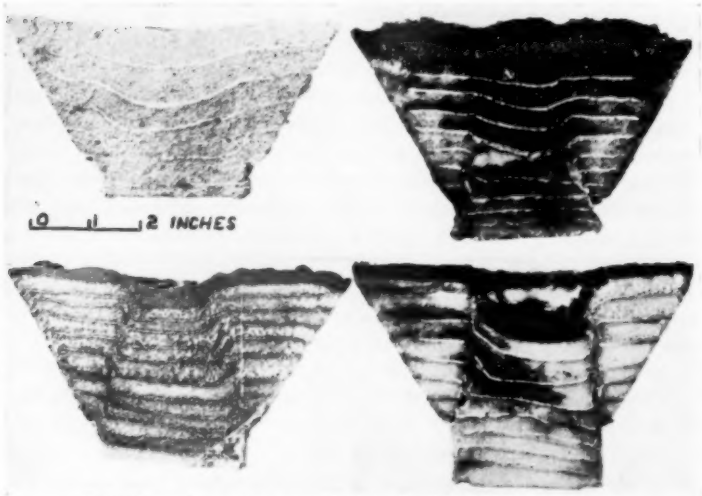
The volcanic sandstone host rock (fig. 1, section BB) lies near the base of Pyroclastic Unit "C" and is the only fluvial bed in the lower part of the unit. The grains making up the bed are well sorted and have a rusty red-brown color not seen in the pyroclastic rocks in the area, so that the bed is distinguishable most of the way around the diatreme.

PLATE 1

A



A. Outcrop of Morale ore body.



B-E. Dynamic models reproducing circular collapse structures.

A surface radiation survey of the diatreme area was made with a scintillation counter, and the results were plotted as an isoradiation map (fig. 1). This map shows anomalous radioactivity wherever the travertine facies of Pyroclastic Unit "C" crops out, with peaks of radiation centered on two outcrops of the ore bed, and on two exposures of cavernous, terrace travertine. Where most radioactive, the travertine averages 0.03 percent U_3O_8 through

a thickness of 15 feet as determined by chemical analysis of a channel sample. The uranium distribution shown on the isoradiation map was followed in a general way by the distribution of a selenium indicator plant, *Astragalus* ("rattlesnake weed").

The presence of large quantities of low-grade mineralized rock in the travertine and of small amounts of ore-grade mineralization in the volcanic sandstone bed near the margins of the diatreme points to a close connection between mineralization and diatreme and suggests that the deposit was formed by hot spring waters. Hot solutions may have reached the surface along fractured zones terminating in spring vents, and also may have been funneled laterally through the permeable volcanic sandstone bed; thus deposition was both syngenetic and epigenetic. The uranium mineral was deposited with the $CaCO_3$ in the travertine terrace, and it may have been precipitated in the sandstone bed by ferric iron. $CaCO_3$ is a good precipitating agent for uranium (Gruner, 1954) and would precipitate uranium at the hot spring vents. It is interesting to note that tyuyamunite occurs (Malde, 1954) in a serpentine-tuff dike near the large Monument Number Two uranium mine in northern Arizona.

CONSTRUCTION OF DYNAMIC MODELS

The structure and the continuity of the ore bed are of prime importance in predicting the location of possible ore bodies, and for this reason it was decided to reproduce the collapse structure of the diatreme with dynamic models. Observation of other diatreme structures by the writer and others (Shoemaker, 1953, Hack, 1942, and Williams, 1936) suggested that at the level exposed the diatreme walls funnel inwards at an inclination of about 60 degrees. Consequently the model form was constructed as a 60-degree truncated funnel with a depressable base. Fifteen models were made in which composition, thickness, shape, and loading were varied in an effort to adjust competency to produce the distribution of structures found in the original. The models were constructed to solidify after deformation so that they could be cut open for examination. Structures reproduced in the models included step faulting in competent beds adjacent to folding in incompetent, radial corrugations in beds (an attempt to deform downwards into the cone by wrinkling), invariable presence of reverse rather than normal faults, and finally the tendency for failure by faulting at depth in the constricted portion of the throat with folding at higher levels.

In plate 1, figures B through E show models arranged in order of increasing competency of material. In the wet cement-sand mixture shown in figure B faulting occurred only in the bottom portion, whereas a broad sag developed in the upper beds. This approximates the general structure assumed for Seth-la-kai. Figures C through E show models made up of mixtures of granulated NaCl and melted paraffin; a "ring dike" of paraffin formed along a concentric reverse fault in the lower portion of figure C.

The structures produced in the models were mechanically similar to those found and postulated in the original, but because overall strength is a

function of size the distribution of structures such as step faults was not identical between models and original.

CONCLUSIONS

No large uranium deposits are predicted for the Seth-la-kai diatreme, but large deposits of similar origin may have been formed by hot springs associated with other Hopi Buttes volcanic centers. The uranium concentration in the thermal waters was apparently too low to form ore-grade syngenetic deposits; therefore commercial-grade epigenetic ore bodies could have been formed only by some precipitating mechanism. The dip of the Morale ore body will progressively steepen towards the center of the structure and the ore bed will finally be faulted downward. The experimental evidence cited suggests that any faults encountered in circular collapse structures will be reverse faults.

REFERENCES

Averitt, Paul, Detterman, J. S., Harshbarger, J. W., Repenning, C. A., and Wilson, R. F., 1955, Revisions in correlation and nomenclature of Triassic and Jurassic formations in southwestern Utah and northern Arizona: Am. Assoc. Petroleum Geologists Bull., v. 39, p. 2515-2524.

Gruner, J. W., 1954, The uranium mineralogy of the Colorado Plateau and adjacent regions: Utah Geol. Soc. Guidebook 9, p. 70-78.

Hack, J. T., 1942, Sedimentation and volcanism in the Hopi Buttes, Arizona: Geol. Soc. America Bull., v. 53, p. 335-372.

Hubbert, M. K., 1937, Theory of scale models as applied to the study of geologic structures: Geol. Soc. America Bull., v. 48, p. 1459-1519.

Hutton, C. O., and Turner, F. J., 1936, Metamorphic zones in northwest Otago: Royal Soc. New Zealand Trans. and Proc., v. 65, p. 405-406.

Lance, J. A., 1954, Age of the Bidahochi formation (abs.): Geol. Soc. America Bull., v. 65, p. 1276.

Malde, H. E., 1954, Serpentine pipes at Garnet Ridge, Arizona: Science, v. 119, p. 618.

Repenning, C. A., and Irwin, J. H., 1954, Bidahochi formation of Arizona and New Mexico: Am. Assoc. Petroleum Geologists Bull., v. 38, p. 1821-1826.

Shoemaker, E. M., 1953, Collapse origin of the diatremes of the Navajo-Hopi Reservation (abs): Geol. Soc. America Bull., v. 64, p. 1514.

Turner, F. J., 1934, Schists from the Forbes range and adjacent country, western Otago: Royal Soc. New Zealand Trans. and Proc., v. 64, p. 161-174.

Williams, Howel, 1936, Pliocene volcanoes of the Navajo-Hopi country: Geol. Soc. America Bull., v. 47, p. 111-172.

INTERNATIONAL RANWICK, LTD.
FIRST NATIONAL BANK BUILDING
DENVER, COLORADO

[American Journal of Science, Vol. 254, July 1956, P. 413-419]

THE FORMATION OF GORE MOUNTAIN GARNET AND HORNBLENDE AT HIGH TEMPERATURE AND PRESSURE

ROBERT H. WENTORF, JR.

ABSTRACT. Using the "Belt" high-pressure apparatus developed in this laboratory, it was found that garnet forms from Gore Mountain hornblende by loss of water at a temperature of about 1250°C. and a pressure above 27,000 atmospheres. Gore Mountain hornblende forms at about 1200°C. at a pressure of at least 22,000 atmospheres. These findings have interesting geological implications.

INTRODUCTION

Although garnet occurs in many places in the Adirondacks, nowhere does it occur in such interesting forms as at Gore Mountain, near North Creek, New York. According to Krieger (1937), the main body of the mountain is syenite. Of great interest is a deposit of garnet-rich rock which occurs near the top of the mountain, and from which garnet is mined (the Barton Mine). This deposit is a narrow mass about three-quarters of a mile long, east-west, and about 200 feet wide, north-south. It touches syenite on the south, gabbro on the north, and anorthosite at each end. There is some garnet and garnet gneiss in the syenite near the main garnet deposit. The deposit itself contains about 10 percent of garnet crystals from one inch to three feet in diameter, often with dodecahedral faces. The garnets are always fractured, and each is completely enclosed by a shell of dark green hornblende. These hornblende-rimmed garnets are scattered in a groundmass which consists of nearly equal parts of hornblende and andesine, together with smaller amounts of biotite, pyroxene, etc. Often between garnet and hornblende there is a thin whitish film of feldspar and biotite. Buddington (1952) and Levin (1950) have made extensive studies of this garnet deposit.

Figure 1 shows garnet lumps and their rock envelopes, and figure 2 shows the feldspar and biotite at the interface between garnet and hornblende.

Garnet is known to melt at about 1100°C. at one atmosphere and refreeze to minerals or glass of lower density than the garnet. The density of garnet is unusually high for a silicate (3.5 to 4.2), and it seems likely that garnet is formed at high pressure. Workers at the Norton Company have found this to be true. Recently Coes (1955) described the synthesis of several high-pressure minerals, including jadeite, kyanite, pyrope, almandite, andradite, and other pure types of garnet. Nearly all these garnets were synthesized from their constituent oxides and water at 900°C. and 10,000 to 30,000 atmospheres. It is noteworthy that attempts to synthesize garnet at relatively low pressures have not yet been successful (Eitel, 1954).

The chemical composition of Barton Mine garnet is, according to Levin (1950):

SiO_2	39.29%
Al_2O_3	22.12
Fe_2O_3	.78
FeO	19.63

CaO	6.16
MgO	11.18
MnO	.38
H_2O^-	.03
TiO_2	.05
Total	99.62

Thus it is mostly almandite and pyrope.

Hornblende is a mineral of somewhat variable composition. It has a relatively high density (3.2) and contains some water as hydroxyl. Experiments in this laboratory showed that a high pressure is necessary to form hornblende from its melt.

According to Levin (1950), a sample of hornblende from the Barton Mine contained:

SiO_2	43.50%
Al_2O_3	13.15
Fe_2O_3	3.39
FeO	9.38
MgO	14.25
CaO	10.58
Na_2O	2.53
K_2O	.68
H_2O	1.15
H_2O^-	.12
TiO_2	1.12
MnO	.09
F	.30
Total	100.24

A sample of hornblende taken from the hornblende shell around a garnet was analyzed in this laboratory and found to contain:

SiO_2	45.1%
Al_2O_3	14.2
FeO, Fe_2O_3	11.7
CaO	9.1
MgO	15.6
Na_2O	3.1
TiO_2	0.9
Total	99.7

It also contained about 1 percent of water as hydroxyl.

EXPERIMENTAL

From a look at the garnetiferous hornblende of Gore Mountain, it seemed possible that the garnet could have formed out of the surrounding hornblende

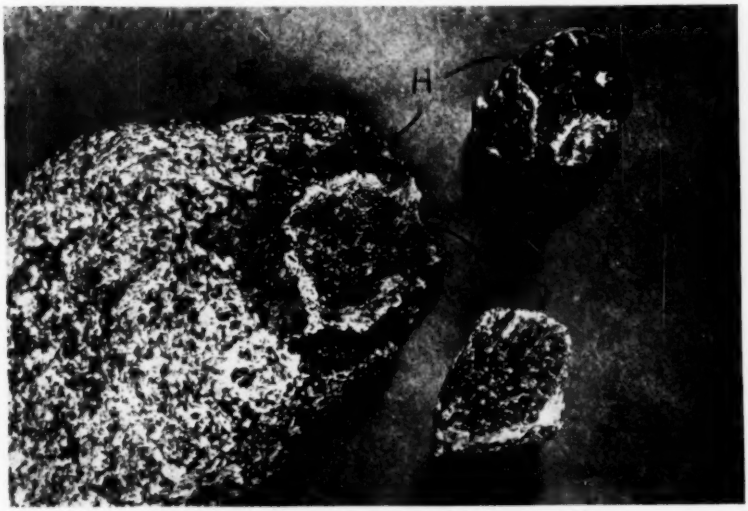


Fig. 1. Gore Mountain garnet rock, 2/3 natural size.
G: Garnet; H: Hornblende; H and F: Hornblende and Feldspar.

at high pressure; the remaining water, silica, alumina, and sodium partly diffused away into the surrounding rock and partly remained at the garnet-hornblende interface to form biotite and feldspar.

Excellent high-pressure and high-temperature equipment capable of testing this hypothesis exists in this laboratory. The experiments that follow were performed in the "Belt" apparatus of Dr. H. T. Hall. This is a pressure vessel containing a capsule with a working volume of about 0.1 ml. The temperature of the capsule is known to within 50°C. from the electrical power used to heat it.

For example, consider an experiment showing the formation of garnet from hornblende. Powdered hornblende was tamped into a metal capsule. (Metal was used because it reacts with water at high pressure and temperature to form hydrogen which escapes from the capsule. Unless water is removed from hornblende, no garnet will form.) The capsule was subjected to a pressure of about 35,000 atmospheres while it was heated to 1450°C., held there a few minutes, slowly cooled (6 minutes) to about 1150°C., and cooled rapidly to 25°C. The pressure was released and the capsule was broken apart and examined under the microscope. Garnet dodecahedra from 2 to 20 microns in diameter were visible, together with hornblende and a little feldspar and biotite. X-ray powder diffraction patterns were made of the products of such an experiment and also of natural hornblende and natural garnet from Gore Mountain. These photographs showed that the hornblende contained hornblende and a little andradite, the natural garnet contained almandite and pyrope, and the products of the experiment contained all the above minerals with unidentifiable traces of others.

As another experiment, consider the growth of large garnet crystals in a temperature gradient. A mixture of powdered garnet and hornblende was tamped into a graphite capsule and exposed to a pressure of 35,000 atmospheres. (Graphite was used because it has a high melting point and is inert

Fig. 2. Photomicrograph of interface between garnet and hornblende in Gore Mountain garnet rock, × 24.
G: Garnet, H: Hornblende; F: Feldspar; B: Biotite.

Fig. 3. Synthetic garnet, × 24.

to these minerals.) The capsule was heated at 1400°C. for about 5 minutes, cooled to 1200°C. in 10 minutes, then cooled rapidly to 25°C. The pressure was released and the capsule was broken up for examination. Here one found that the cooler ends of the capsule contained several dozen yellow garnet crystals embedded in a fragile matrix. Figure 3 is a photomicrograph of these garnets. An edge of a millimeter scale is visible for comparison. Toward the midlength of the capsule were no garnets, but instead a mixture of powdery hornblende and lumps of a yellow hydrated glass which puffed up on heating to 1000°C.

As yet another typical experiment, consider the formation of hornblende from garnet and water. Crushed garnet was tamped into a graphite capsule and moistened with water. The capsule was subjected to 35,000 atmospheres pressure and heated at 1400°C. for about 6 minutes, cooled to 1150°C. in 13 minutes, then cooled rapidly to 25°C. The pressure was released and the capsule was examined. At its bottom end appeared a fragment of synthetic garnet about 1 mm square embedded in a crumbly glass. In the midlength of the capsule were many fragments of synthetic hornblende about 20 to 100 microns in diameter. Since the garnet contains very little alkali, the hornblende made from it must be mostly the alkali-poor variety.

SUMMARY

After about forty experiments along these lines it was possible to assemble the following facts about the formation of garnet and hornblende.

1. At temperatures between 1200 and 1300°C. and pressures between 27,000 and at least 40,000 atmospheres a complex equilibrium exists:

Melt, Hornblende $\rightleftarrows$ Melt, Water, Garnet, Biotite, Feldspar

A change of pressure between 27,000 and 40,000 atmospheres does not change the equilibrium much. As the temperature is lowered from 1400°C. garnet crystallizes first at about 1250°C. Thus it forms in regular crystals and grows in the cool end of a capsule. Unless water is removed from hornblende no garnet will form. Below 1150°C. the melt is essentially frozen, and no formation or destruction of hornblende can be noticed in half an hour at 35,000 atmospheres. The effect of pressure above 40,000 atmospheres on the equilibrium was not studied.

2. Between 22,000 and 27,000 atmospheres, garnet will not form from molten hornblende, and one finds the capsule filled with recrystallized hornblende. If the melt is cooled too quickly, there forms a clear yellow glass containing dendrites, mostly of hornblende. The clear glass shows no crystallinity in an X-ray powder diffraction pattern.

3. Between 15,000 and 22,000 atmospheres the hornblende melt solidifies to a complex mixture of hypersthene, pyroxene, and other unidentifiable minerals, according to an X-ray diffraction pattern. If the melt is cooled faster than 20°C. per minute, only glass forms.

4. A mixture of Gore Mountain garnet and the feldspar-hornblende-biotite rock forming the mass of the mountain solidifies to a brown glass below a pressure of about 27,000 atmospheres. At pressures between 27,000

and 40,000 atmospheres garnet forms from such a melt at about 1200°C., together with brown and yellow glass. The melt could not be cooled slowly enough to obtain crystals instead of glass.

5. Large crystals of garnet can be grown at pressures between 27,000 and 40,000 atmospheres. The raw material for the melt can be made up of garnet and hornblende, or garnet and Gore Mountain rock, or garnet and water. The garnets form at the cool end of the capsule. The largest garnet grown so far was about 1 mm in diameter. Its size was limited by the size of the capsule.

6. The andesine-hornblende mixture in which the hornblende-surrounded garnets are found melts about 50° lower than the hornblende alone. No garnet forms from this melt unless water is removed from it while the pressure exceeds 27,000 atmospheres.

7. If a hornblende melt is cooled slowly at 22,000 atmospheres, there forms a mixture of glass and hornblende. If a hornblende melt is cooled at the same rate at 27,000 atmospheres, nearly all hornblende is formed with very little glass. Certainly viscosity rises with pressure, so that if diffusion limited crystal growth one would expect fewer, smaller crystals at the higher pressure. But at the higher pressure there is a greater free energy difference between glass and hornblende, and this, not diffusion, must control the rate of crystal growth.

Again, it is possible to grow well formed 20-micron garnets from hornblende by cooling from 1350°C. to 1100°C. in 30 seconds. This implies a relatively fluid melt, almost like water, for the time available to grow the garnets is about 15 seconds.

It is interesting that these silicate melts have such low viscosities at such high pressures. By way of comparison, some molten, nearly anhydrous volcanic lavas have viscosities about 100 times that of honey, and Bridgman found that the viscosity of hexane increases thirty-fold when the pressure on it is increased from 1 to 8000 atmospheres at 30°C. Such comparisons illustrate the solvent powers of water.

DISCUSSION

It is tempting to suppose that the garnet of Gore Mountain formed under conditions similar to those in the laboratory, and some arguments exist favoring this hypothesis. However, many gaps remain in our knowledge about this mineral system; the most serious of these are the combined effects of low temperature (400-600°C.) and long time (months or years). Perhaps under such conditions garnet could form at low pressures of a few thousand atmospheres. Until this mineral system is thoroughly explored, the genesis of the garnet of Gore Mountain must remain uncertain.

Perhaps from a study of the pressure-temperature dependence of the garnet-hornblende equilibrium it will be possible to set a lower pressure limit below which garnet cannot form even at 100°C. Whether such a pressure-temperature equilibrium line can be followed sufficiently far depends on the

as yet unknown rate of approach to equilibrium in such a system. Further studies are planned along these lines.

References

Buddington, A. F., 1952, Chemical petrology of some metamorphosed Adirondack gabbroic, syenitic, and quartz syenitic rocks: Am. Jour. Sci., Bowen v., p. 37-84.

Coes, Loring, Jr., 1955, High pressure minerals: Am. Ceramic Soc. Jour., v. 38, p. 298. (Also, Silica Symposium, Rutgers University, June 4, 1954.)

Eitel, W., 1954, The physical chemistry of the silicates: Chicago, Univ. Chicago Press.

Hall, H. T., The "Belt" ultra high-pressure, high-temperature apparatus: (to be published).

Krieger, M. H., 1937, Geology of the Thirteenth Lake quadrangle: New York State Mus. Bull. 308.

Levin, S. B., 1950, Genesis of some Adirondack garnet deposits: Geol. Soc. America Bull., v. 61, p. 519-565.

General Electric Research Laboratory
Schenectady, New York

[American Journal of Science, Vol. 254, July 1956, P. 420-428]

THE ISOTOPIC VARIATION OF COMMON LEAD IN GALENA FROM THE FRONT RANGE AND ITS GEOLOGICAL SIGNIFICANCE*

GEORGE PHAIR and HENRY MELA, JR.

ABSTRACT. Lead extracted from 13 samples of galena from the Colorado Front Range was analyzed mass spectrometrically. These samples included 9 from the major districts in the Laramide mineral belt, 3 from "higher temperature" deposits of controversial ages from outlying parts of the Range, and one from the pegmatite of Stove Mountain of definite Pikes Peak age (late Precambrian). The results show that: (1) Galena samples from the southwestern half of the Laramide mineral belt as compared with the northeastern half are enriched in Pb^{206}, Pb^{207}, and Pb^{208} relative to Pb^{204}; (2) the three galena samples from the deposits in the outlying parts of the Front Range have isotopic compositions typical of older Precambrian common lead and widely different from all Late Cretaceous or younger lead so far reported in the literature—a fact that in large measure substantiates the Precambrian age of the deposits inferred by Lovering and Goddard; and (3) as might be expected, the composition of the lead in galena from the pegmatite of Stove Mountain is intermediate between that of the Laramide and that of the earlier Precambrian lead.

As in the Colorado Plateau lead samples studied by Stieff and Stern, the regional averages for Pb^{208} and Pb^{207} in the Front Range along the Laramide mineral belt increase from east to west. Unlike the lead from the Colorado Plateau, however, thorium-lead (Pb^{208}) increases with the uranium leads (Pb^{206} and Pb^{207}). No Pb^{208} enrichment was noted in galena from *nonuraniferous* veins in and around centers of intrusion of uranium-rich late-stage Tertiary intrusives or in actual uraniferous mining districts.

INTRODUCTION

During the 1952 field season, fresh galena was collected from 26 mines in the Colorado Front Range as part of a comprehensive study of the geological cycle of uranium and related elements in this region carried on since 1949 by the U. S. Geological Survey on behalf of the U. S. Atomic Energy Commission. A special effort was made to obtain samples from mines then in operation. Most of the galena was coarsely crystallized, and hand-picked separates weighing 200-500 mg and free from other sulfides and alteration products were readily obtained. All exposed surfaces were chipped off and only the inner part of each fragment was used. Thirteen samples of those collected were selected for isotopic study. As a check on possible contamination, 12 of these 13 samples were analyzed chemically for uranium (table 1). Uranium was found to be negligible for the present purposes in all 12 samples. Lead separated from each of these samples as the iodide was analyzed isotopically by the Mass Assay Laboratory of the Carbide and Carbon Chemical Company's Y-12 Plant, Oak Ridge, Tennessee, using modified Nier-type spectrometers. The samples were analyzed in the sequence indicated by the numbers in tables 1 and 2.

These isotope-abundance studies were integrated with the broader investigations of common lead variation in the Colorado Plateau deposits carried on by L. R. Stieff and T. W. Stern of the Geological Survey. We are indebted to these workers and to R. S. Cannon, Jr., of the Geological Survey, for numerous helpful suggestions in the course of the study. Most of the samples were collected by Phair assisted by Norman Herz. One sample (GS 3) was collected by R. U. King and Phair during the summer of 1949. Mela

* Publication authorized by the Director, U. S. Geological Survey.

made the chemical analyses and separated the lead iodides for mass spectrometric study.

TABLE 1
Uranium Content of Galena Samples

Sample no.	Percent U (chemical)
GS/177	0.00080
GS/266	0.00071
GS/267	0.00104
GS/268	0.00069
GS/269	0.00092
GS/270	0.00074
GS/271	0.00035
GS/272	0.00065
GS/274	0.00053
GS/275	0.00027
GS/276	0.00046
GS/277	0.00031

TABLE 2
Results of Isotopic Analyses of Common Lead Expressed in Percentages

Sample no.	District, Mine	Pb^{204}	Pb^{206}	Pb^{207}	Pb^{208}
GS/3	Caribou, Caribou	1.43	24.16	21.54	52.86
GS/177	Central City, Eureka	1.39	24.99	21.31	52.31
GS/266	Silver Plume, Smuggler	1.35	24.00	21.21	53.43
GS/267	Idaho Springs, Stanley	1.36	24.86	21.34	52.44
GS/268	Cotopaxi, Cotopaxi	1.49	23.49	22.73	52.28
GS/269	Guffy, Lone Chimney	1.52	23.35	22.68	52.44
GS/270	Breckenridge, Wellington	1.38	24.98	21.34	52.30
GS/271	Central City, Franklin-Silver Age	1.39	24.60	21.43	52.58
GS/272	Bergen Park, Blackmoor's	1.51	23.34	22.80	52.34
GS/274	Argentine, Waldorf	1.35	24.94	20.97	52.73
GS/275	Lawson, Bellevue	1.38	24.72	21.23	52.66
GS/276	Gold Hill, Yellow Pine	1.40	24.22	21.38	52.99
GS/277	El Paso County, Stove Mt. Peg.	1.45	24.01	22.13	52.40

GALENA FROM THE LARAMIDE MINERAL BELT

The general geology of the region has been described by Lovering and Goddard (1950). Nine samples representing most of the large districts in the Laramide mineral belt were among those analyzed. These came from mines scattered over the length of the belt. (fig. 1). The sample spacing was closest in the middle part of the Front Range where uranium in the porphyries of Laramide age and in the associated veins has been found to reach a regional high. The distribution of uranium and of radioactivity in these early Tertiary dike rocks through a large part of the mineral belt is known from radiometric and uranium analyses of more than 400 samples of the porphyry collected in the field and studied in the laboratory (Phair, 1952; also summary report

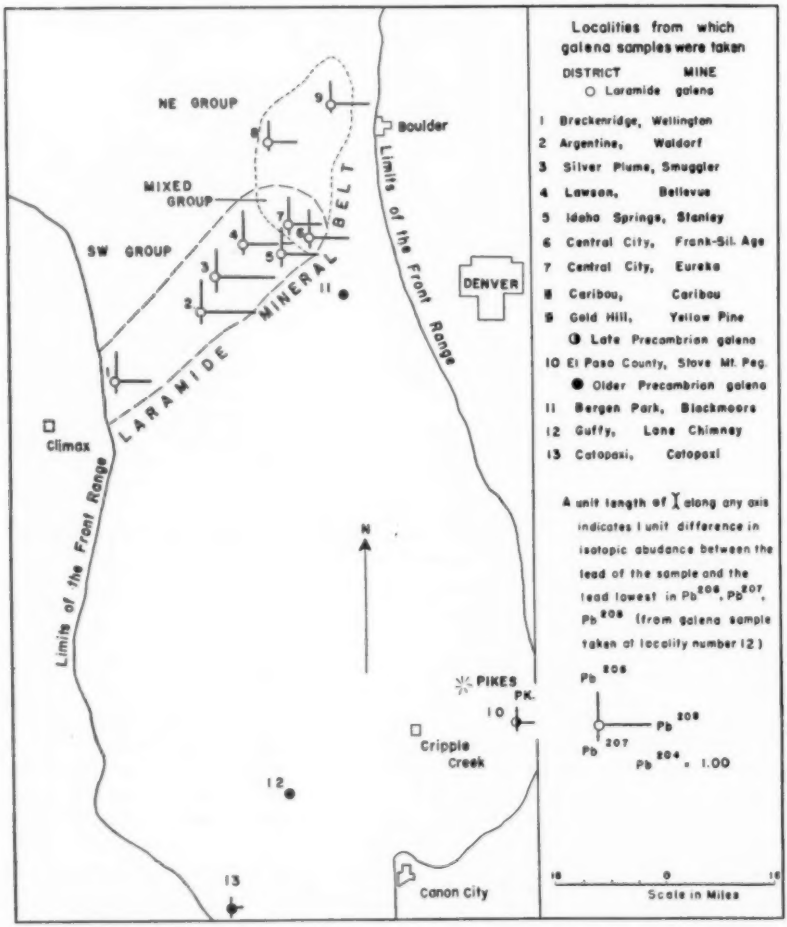

Localities from which galena samples were taken
DISTRICT MINE
○ Laramide galena
1 Breckenridge, Wellington
2 Argentine, Waldorf
3 Silver Plume, Smuggler
4 Lawson, Bellevue
5 Idaho Springs, Stanley
6 Central City, Frank-Sil. Age
7 Central City, Eureka
8 Caribou, Caribou
9 Gold Hill, Yellow Pine
◑ Late Precambrian galena
10 El Paso County, Stove Mt. Peg.
● Older Precambrian galena
11 Bergen Park, Blackmoore
12 Guffy, Lone Chimney
13 Catopaxi, Catopaxi
A unit length of X along any axis indicates 1 unit difference in isotopic abudance between the lead of the sample and the lead lowest in Pb206, Pb207, Pb208 (from galena sample taken at locality number 12)
Pb 208
Pb 207
Pb 204 = 1.00
NE GROUP
MIXED GROUP
SW GROUP
MINERAL BELT
LARAMIDE
Limits of the Front Range
Boulder
DENVER
Climax
PIKES PK.
Cripple Creek
Canon City
N
Scale in Miles

Fig. 1. The isotopic variation of common lead in galena from the Colorado Front Range.

in preparation). The trend of differentiation in the same rocks has been worked out on the basis of results of 50 standard rock analyses by rapid methods coupled with petrographic study. Besides filling gaps in the regional isotopic pattern as described by Stieff and Stern (personal communication), these isotopic studies had an additional objective. We hoped to find out whether in this region lead from areas in and around the centers of intrusion of lime-poor rhyolite known to be enriched in uranium (rocks having as much as 20 times the uranium content of normal calc-alkaline granite) showed an unusually high content of the uranium daughter Pb^{206}. Throughout the

mineral belt we have noted evidence of close space, time, and geochemical connections linking these uranium-rich igneous rocks—the lime-poor rhyolite —with actual deposits and showings of pitchblende (Phair, 1952).

Both uranium and lead tend to be concentrated in late-stage differentiates and in hydrothermal solutions. Assuming that the common ancestor of the porphyries and the associated vein deposits was a magma initially uraniferous formed by remelting or assimilation of older rocks that were themselves uranium-rich, it seems reasonable to suppose that the concentration of uranium and of the uranium daughter Pb^{206} should go hand in hand. A close association in space and time might be expected, therefore, among late-stage differentiates enriched in uranium, vein galena enriched in the isotope Pb^{206}, and actual deposits of pitchblende. If so, the Pb^{206} abundance might serve not only as permissive indication of the uranium potential in a given area but might also throw new light on the age-old question of the origin of magmas.

It should be remarked at the outset that this brief investigation was ***not*** designed to test whether the common lead from galena closely associated with uranium minerals *in the same vein* contained unusually large amounts of Pb^{206}. That such local enrichment may occur is clear from the studies of galena from (1) the Ace Creek mine (Collins, Farquhar, and Russell, 1954, table 1, p. 7); (2) the Witwatersrand, (op. cit., table 1, p. 11); and (3) the Happy Jack mine, Utah, (L. R. Stieff and T. W. Stern, personal communication). With one exception we intentionally avoided collecting galena from veins known to be uraniferous, because some such lead samples may reflect post-depositional introduction of Pb^{206}. We were interested in the composition of the common lead at the time of original deposition and in the relationship of that composition to the last stages of magmatic differentiation.

The data presented in this paper (tables 2 and 3) show only that the Pb^{206} content of the galena and the uranium content of the associated igneous rocks are not related in any simple way. Our sampling has been too incomplete and the analytical errors are too great to permit the drawing of fine distinctions.

Table 3 and the sketch map (fig. 1) show that the isotopic compositions do fall into a geographic pattern, which bears little relationship, however, to the spatial distribution of radioactive igneous rocks and uraniferous veins. Two galena samples from the northern part of the mineral belt, an area containing numerous radioactive centers of intrusion and abundant small showings of uranium, are poorest in Pb^{206}. Two from the central part of the belt, the area richest in uraniferous late-stage differentiates and in workable uranium deposits, have mixed characteristics—both are enriched in Pb^{206}, one is enriched in Pb^{207}, and neither is enriched in Pb^{208}. Five galena samples from the southern part of the belt, the area poorest in radioactive intrusions and in actual showings of pitchblende, are enriched in all three radiogenic isotopes as compared with those in the north. This geographic pattern is evident in spite of any experimental error that can be reasonably expected to be present. The pattern for Pb^{207} is less well defined than for Pb^{206} and Pb^{208} because of its limited variability. Pb^{207} cannot vary independently of Pb^{206}, a small change in the one being accompanied by a much larger change

TABLE 3

Isotopic Variation in Common Lead from the Front Range, where $Pb^{204} = 1.00$

(Samples listed from northeast to southwest on map.)

Lead sample no.	Locality no. (on map)	Mine	Pb^{206}	Pb^{207}	Pb^{208}	Excess over GS/269 Pb^{206}	Excess over GS/269 Pb^{207}	Excess over GS/269 Pb^{208}	
			Laramide galena						
GS/276	9	Yellow Pine	17.30	15.27	37.85	1.94	0.35	3.35	Less enriched
GS/3	8	Caribou	16.89	15.06	36.96	1.53	0.14	2.46	
GS/177	7	Eureka	17.98	15.33	37.63	2.62	0.41	3.13	Mixed
GS/271	6	Franklin-Silver Age	17.70	15.42	37.83	2.34	0.50	3.33	
GS/267	5	Stanley	18.28	15.69	38.56	2.92	0.77	4.06	
GS/275	4	Bellevue	17.91	15.38	38.16	2.55	0.46	3.66	
GS/266	3	Smuggler	17.78	15.71	39.58	2.42	0.79	5.08	More enriched
GS/274	2	Waldorf	18.47	15.53	39.06	3.11	0.61	4.56	
GS/270	1	Wellington	18.10	15.46	37.90	2.74	0.54	3.40	
			Late Precambrian galena						
GS/277	10	Stove Mt. pegmatite	16.56	15.26	36.14	1.20	0.34	1.64	
			Older Precambrian galena						
GS/272	11	Blackmoor's Ranch	15.46	15.10	34.66	0.10	0.18	0.16	
GS/269	12	Lone Chimney	15.36	14.92	34.50	0.00	0.00	0.00	
GS/268	13	Cotopaxi	15.76	15.25	35.09	0.40	0.33	0.59	

* This solid line makes a separation, without overlap, between lead samples less enriched in Pb^{206} and lead samples more enriched in Pb^{206}. A similar separation of the samples is made in each of the next two columns on the basis of Pb^{207} content and Pb^{208} content, respectively.

in the other. In table 3, solid lines divide the lead samples into two groups without overlap on the basis of isotope content—one group less enriched and one more enriched, with respect to each isotope. It will be noted that the point at which the division is made is not the same for all three isotopes, and that the slight difference in position of the dividing lines in the separate columns gives rise to the intermediate group of lead samples with mixed characteristics. The precise position of the dividing line which separates the lead samples into two groups on the basis of Pb^{207} content may be open to some question. The distinction between enriched and unenriched galena with respect to Pb^{206} and Pb^{208} is much more pronounced and less subject to error. The "maverick" in the geographical pattern is the Pb^{208} in sample GS/270; it is definitely low. The associated Pb^{206} and Pb^{207} from the same galena sample conform to the regional trend. Possibly more detailed sampling would have revealed other erratics, but in terms of regional averages the trend seems clear. No internal trends are evident within any one of the three groups.

The observed pattern represents the eastward beginnings of a geographic pattern first noted by Stieff and Stern (personal communication) in the region to the west of the Front Range. On the basis of isotopic analyses of some 45 samples of lead minerals, chiefly from the Colorado Plateau and from the San Juan Mountains, they concluded that samples from any one area may show considerable variation but the regional averages for the content of Pb^{206} increase in a westward direction. All their samples contain more Pb^{206} than the most highly enriched galena from the Front Range. In contrast to the Pb^{208} in the lead minerals studied by Stieff and Stern (personal communication), however, Pb^{208} in the Front Range lead minerals also increases relative to Pb^{204}.

The differences in isotopic composition between lead minerals from the northeastern and southwestern Front Range are much too large to be attributed to small differences in time of deposition. Lovering and Goddard (1950) have postulated that the "deep" parent magma, which in Laramide times underlay the northeastern half of the belt, differed in composition from that beneath the southwestern half. To the extent that the isotopic differences may reflect differences in lead and uranium contents of the source rocks from which these magmas were derived, these results are consistent with that interpretation.

In its low ratios of Pb^{206}, Pb^{207}, and Pb^{208} to Pb^{204}, the Laramide lead from the Caribou mine approaches a late Precambrian lead in composition (cf. lead from the Stove Mountain pegmatite, table 3). Kerr and Kulp (1952) in their determination of the Pb^{206}/U^{238} age of uraninite from the Caribou mine made a generalized common lead correction and calculated an apparent age of 23 ± 10 million years. Using the actual lead from this mine in making the common lead correction, we calculated an apparent Pb^{206}/U^{238} age of 37 million years for the same sample. Because the sample analyzed by Kulp contained about 97 percent of the total lead as common lead, the mass spectrometer error becomes multiplied many fold in making any common lead deduction and a maximum uncertainty of about 14 million years is introduced into the age calculations that can be made. Considering only these

sources of error the possible Pb^{206}/U^{238} age of this sample ranges from 23 to 51 million years. The upper limiting age is close to the average Pb^{206}/U^{238} age obtained on uraninites from the Central City district by several workers. Little confidence can be attached to these results on the Caribou samples. More and better samples are needed.

PRECAMBRIAN GALENA

Like common lead forming today, the original lead present in the Earth's crust is believed to have consisted of the isotopes Pb^{204}, Pb^{206}, Pb^{207}, and Pb^{208}. The last three of these isotopes are also produced by processes of radioactive decay; the Pb^{204} is nonradiogenic so far as is known. Throughout the Earth's history the original lead has become increasingly enriched relative to Pb^{204} in all three radiogenic isotopes derived from the breakdown of U^{238}, U^{235} and Th^{232}. Addition of the radiogenic components has been facilitated by basic geological processes—magmatic, hydrothermal, and supergene. As a result the isotopic composition of the lead tends to reflect the geological age of the mineral assemblage in which it is now found and to which it is genetically related. The percent Pb^{204} in any lead sample (table 2) thus provides an index of its "primitiveness." Just what this index will mean in terms of absolute age depends upon geographical and geological factors, but it is generally true that the oldest leads have the highest Pb^{204} contents.

No claim is made that the isotopic composition of common lead will permit a quantitative estimate of age in terms of millions of years. Moreover, an inspection of the table "Relative isotopic abundances of common leads" (Faul, 1954) reveals several exceptions to the rule that Precambrian lead is characterized by primitive compositions. The same data show, however, that these exceptions are limited to certain lead of probable *late* Precambrian age (e.g., some at Sudbury) or to lead from deposits known to be uraniferous (e.g., Witwatersrand). These exceptional lead samples seem to be local developments typical of certain mines. In two of the four Sudbury mines in which these enriched leads are found, lead having the more usual late Precambrian characteristics is also present. The lead from Witwatersrand is characterized by Pb^{206}/Pb^{204} ratio far in excess of the Pb^{208}/Pb^{204} ratio, the reverse of what is found in leads from nonuraniferous deposits.

In the anomalous Precambrian leads so far reported the isotopic enrichment involves only the uranium lead; the associated thorium lead is present in the abundance expected in old-age galena. The Front Range galena samples from ore deposits outside the Laramide belt in contrast to those from within the belt are remarkably uniform in composition and definitely primitive with respect to content of all three radiogenic isotopes. The published data reveal no instance of isotopic overlap of any kind between lead of definite *older* Precambrian[1] age from nonuraniferous veins and lead of definite Laramide age—the only age distinction we are attempting to draw in this paper. It

[1] By "older" Precambrian lead we mean lead of a definitely more primitive composition than lead from a late Precambrian pegmatite of Pikes Peak type the "absolute" age of which is reasonably well known. So used, the term "older" Precambrian is probably synonymous with early to middle Precambrian.

might be argued that one should be cautious about using the relative primitiveness even on a broad scale as an age indicator because geographical trends not yet suspected may eventually turn up. In the present studies, however, we are concerned not with global or continent-wide generalizations but with relationships in a single small region the geology of which has been under study for 50 years. Our data have been obtained not on single samples but on sets of samples, and within each set the samples have been so spaced as to provide an estimate of the effect of geographical isotopic variation. The geographical variation evident among the three samples of unknown age is extremely small. The differences in isotopic composition between these and the samples from the Laramide mineral belt are much too large and much too systematic to be attributed to analytical or sampling errors. The results are in harmony both with the predominant world-wide isotopic pattern and with what is, in our opinion at least, the bulk of the geological evidence.

Scattered through parts of the Front Range outside the Laramide mineral belt are several ore deposits of unknown age thought to be Precambrian by Lovering and Goddard (1950). Recently several geologists have voiced the opinion that these deposits represent only a deeper and higher-temperature phase of the Laramide metallization.

Many of these deposits have been mined in a small way for base metals, chiefly copper and zinc. Unlike most of the ores known to be Laramide these ores consist of massive sulfides in a gangue of rock-forming silicates, particularly pyroxenes and hornblendes. The "high-temperature" metallics—magnetite, pyrrhotite and iron-rich sphalerite—are scattered in these deposits but are locally abundant. The ore bodies themselves are lenticular, foliated to banded, and more or less conformable with the enclosing gneisses. During the summer of 1952 Phair visited 14 of the 18 deposits described by Lovering and Goddard (1950). Galena was found to be very scarce in most of the 14 with the exception of those near the southern limit of the range (Cotopaxi, Lone Chimney, and Isabel). Fortunately we were able to collect fresh galena from 3 of the 4 subtypes recognized by Lovering and Goddard. Of the 4 deposits from which the galena obtained was isotopically analyzed, one—Cotopaxi—has been interpreted as a magmatic segregation in mafic rocks; two, Lone Chimney and Bergen Park, as high-temperature replacements; and one, Stove Mountain, as an occurrence of primary galena in granite pegmatite (J. W. Adams, personal communication). Two of these deposits—Cotopaxi and Lone Chimney, now the Bessie—were being actively worked in 1952.

The age of the pegmatite of Stove Mountain is definitely late Precambrian. This pegmatite is a differentiate of the closely associated, largely undeformed Pikes Peak granite, which cuts foliated crystalline rocks and which has been dated within the limits of 800 to 900 million years by several laboratory methods. The isotopic composition of the galena from this pegmatite is consistent with a late Precambrian age but of itself does not rule out entirely an early Paleozoic age. This galena supplied by J. W. Adams, U. S. Geological Survey, was doubly valuable. Not only is syngenetic galena extremely rare in pegmatites but in addition the sample provided a relatively fixed point on the geological time scale for the late Precambrian in this region with which

to compare our other results. The galena was present as isolated cubes as large as half an inch on an edge in an aggregate of coarse microcline and quartz with smaller euhedra of zircon and sphene. No other recognizable sulfides nor any hydrothermal gangue minerals were present. The large cubes were covered with a whitish film which extended into the adjacent silicates, but when the cubes were broken open the inner parts were found to be completely fresh.

Figure 1 shows that the three other lead samples (11, 12, 13) from outside the belt differ markedly in isotopic composition from all those collected from mines located within the belt. In addition these lead samples from outside the belt have (1) distinctly lower contents of Pb^{206} and Pb^{208} but higher Pb^{204}, and (2) nearly equal parts of Pb^{206} and Pb^{207}. These attributes are consistent with, and in a large measure confirm, the older Precambrian ages of all three samples. For the purposes of comparison the isotopic composition of galena believed to be middle Precambrian (1300 million years) by Nier (1938) is as follows:

	Pb^{204}	Pb^{206}	Pb^{207}	Pb^{208}
Galena, Great Bear Lake	1.00	15.93	15.30	35.30

Age determinations by lead-uranium, lead-thorium and lead-lead methods upon primary uraninite from a pegmatitic syenite intrusive into the basement complex in the Central City district and alpha-lead determinations upon zircon from the same intrusive indicate that the middle Precambrian was a time of igneous activity in that part of the Front Range at least. These three galena samples may be older but probably are not much younger than the age found 1300 ± 100 million years (Phair and Gottfried, manuscript in preparation). In contrast to the Laramide lead samples the older Precambrian lead samples show little geographic variation; two samples of galena from similar deposits 65 miles apart are so nearly identical that the differences cannot be plotted on the scale of the sketch map (fig. 1, nos. 11 and 12). The third of the older Precambrian galena samples shows a very slight enrichment in radiogenic components as compared to the other two, but the difference is of the same order as the expected experimental error.

References

Collins, C. B., Farquhar, R. M., and Russell, R. D., 1954, Isotopic constitution of radiogenic leads and the measurement of geological time: Geol. Soc. America Bull., v. 65, p. 1-22.

Faul, Henry, ed., 1954, Nuclear geology: New York, John Wiley & Sons, p. 284-292.

Kerr, P. F., and Kulp, J. L., 1952, Pre-Cambrian uraninite, Sunshine Mine, Idaho: Science, v. 115, p. 86-88.

Lovering, T. S., and Goddard, E. N., 1950, Geology and ore deposits of the Front Range, Colorado: U. S. Geol. Survey Prof. Paper 223.

Nier, A. O., 1938, Variations in the relative abundance of the isotopes of common lead from various sources: Am. Chem. Soc. Jour., v. 60, p. 1571-1576.

Phair, George, 1952, Radioactive Tertiary porphyries in the Central City district, Colorado, and their bearing upon pitchblende deposition: U. S. Geol. Survey TEI-247, U. S. Atomic Energy Comm. Tech. Inf. Service, Oak Ridge, Tenn.

U. S. Geological Survey
Washington 25, D. C.

[American Journal of Science, Vol. 254, July 1956, P. 429-432]

GEOGRAPHIC NAMES FOR MEMBERS OF THE BRULE FORMATION OF THE BIG BADLANDS OF SOUTH DAKOTA

JAMES D. BUMP

ABSTRACT. The Brule formation as it is exposed in the Big Badlands of South Dakota is divided into two members. The lower member, which includes a major part of the classic *Oreodon* beds, is designated the Scenic member and subdivided into two units; the upper portion, which includes the *Protoceras-Leptauchenia* beds, is designated the Poleslide member and subdivided into three units.

The Brule formation, defined by Darton (1899, p. 736), includes the part of the White River Oligocene which overlies the Chadron formation. A standard section was not specified, but classically these deposits were studied and described from the Big Badlands of southwestern South Dakota, the type area of the White River group. The Brule formation had originally been termed Turtle and *Oreodon* beds by Hayden (1857, p. 153) and *Oreodon* beds by Hayden (1867, p. 59) but was later subdivided by Wortman (1893) into the *Oreodon* beds (lower unit) and *Protoceras* beds (upper unit). The *Protoceras* beds have also been called the *Leptauchenia* beds and the *Protoceras-Leptauchenia* beds. All of these terms have become deeply rooted in Oligocene literature.

Schultz and Stout (1938) proposed the name Orella member for the lower or *Oreodon* portion and Whitney member for the upper or *Leptauchenia* portion of the Brule formation as it occurs in northwestern Nebraska. Oligocene outcrops do not continue unbroken between the Big Badlands and the closest exposures in Sioux County, Nebraska. Toadstool Park, which lies just west of Orella Station, Sioux County, Nebraska, is more than 50 miles from the nearest complete Brule section in South Dakota. The scattered intermediate outcrops are of such limited vertical and linear extent as to make them of little stratigraphic use.

The lithology of the Brule formation, as displayed in the Scenic Basin of the Big Badlands, has a remarkable uniformity over a large area. But regardless of this, there is often considerable lateral variation in composition, structure, texture, color, and hardness of the strata. Numerous areas exhibit gradual changes in lithology but in other places changes are extreme over very short distances. The greater and more abrupt variations in lithology occur mainly in the north-south rather than the east-west direction. This would seem normal since several roughly parallel Oligocene streams flowed in an easterly direction, depositing their sediments in more or less separate areas. The streams may have risen in the same general region but their loads were composed of different or varying percentages of numerous types of source rocks. The load, volume, and velocity of a stream determine the physical aspects of its deposits. These factors cannot be identical in two or more stream systems. Therefore the clays, sandstones, concretions, kinds and amounts of cementing materials, etc., of the Oligocene badlands, as we find today, are not identical over very great distances. It is not surprising, then, that lithologic

correlations between member units within the Brule formation have not been made with any degree of accuracy among widely spaced areas. The lithologic boundaries of the Nebraska Oligocene do not appear to correspond closely with the lithologic boundaries of the South Dakota Oligocene. It is problematical whether exact correlations can ever be made.

Wortman, in making his subdivision of the strata of the Big Badlands, considered the boundary between the *Oreodon* beds and the *Protoceras* beds to be approximately 100 feet of barren, light-colored clays. Wanless (1923, p. 226) recognized this division but placed the contact at a "light weathering band" which occurs occasionally in the upper part of these clays.

Most field workers in recent years have attempted to follow the classification of Wanless and, in order to more closely tie in the fauna, have used a subdivision of the *Oreodon* beds into lower, middle, and upper zones. The lower and middle zones have been easily recognized as the lithology and the boundaries are uniform and distinct. However, the extent of the upper unit (upper *Oreodon* bed) has always been exceedingly difficult to determine because of locating the upper limit, i.e. the "light weathering band." This light gray band is oftentimes absent or, if present, poorly defined. Quite frequently several similar bands exist near the proximity of the contact. This makes it almost impossible, even for a worker experienced in the region, to determine with any precision the correct boundary marker.

The *Protoceras* channel sandstones produce a fauna that has long been considered Whitneyan in age. In at least one area of the Big Badlands these channels cut into the "upper *Oreodon* beds" to a depth of more than 30 feet. This should present no age problem but some workers have considered the fauna of these lower channels as of Orellan age.

It seems essential at this time to designate standard sections and assign geographic names for the subdivisions of the Brule formation of the Big Badlands of South Dakota, which have, in part, been recognized as members. These fall, respectively, within the Orellan and Whitneyan provincial ages as established by Wood et al. (1941), which, in intention, were defined primarily by the faunas of these two units.

The unit formerly known as the *Oreodon* beds (Wortman), minus the upper *Oreodon* bed, is hereby designated the Scenic member. The following standard section is in the SW¼ Sec. 23 T. 3 S. R. 13 E., two and two-tenths miles south of Scenic, Pennington County, South Dakota.

Feet	Description
	Upper Nodular Zone
12	Light cream-colored clays with narrow layer of fossiliferous clay-lime concretions. Lime content of latter higher than in those of the lower nodular zone and with little oxidation on their surfaces. Overlain by upper Brule clays.
22	Gray clays with scattered and rounded silt concretions containing few fossils. Near-vertical weathering.
89	Mostly gray clays but with irregularly spaced brown banding and containing bedded, lens-shaped silt concretions. Fossils rare.

Lower Nodular Zone

Feet	Description
36	Pink-gray clays weathering on the surface to brown-gray color. Contains numerous clay-lime concretions which oxidize to rusty color on surface. Highly fossiliferous. Underlain by Chadron limestone and clays.

The Chadron-Brule contact is easily identifiable here and the lower and upper concretions are well developed. *Metamynodon* channel sandstones are absent but occur two miles to the south. This member is conveniently divided into two units; the lower and upper nodular zones. There has never been any difficulty in recognizing the lower nodular zone; its lithology is remarkably uniform throughout the Big Badlands. This is also true of the upper nodular layer, and thus the Orellan-Whitneyan contact may be located without difficulty.

The unit known as the *Protoceras* beds (*Leptauchenia* beds) is designated the Poleslide member. The standard section is in the NW¼ Sec. 23 T. 43 N. R. 44 W., eight and one-half miles south of Scenic, South Dakota and on the south rim of Sheep Mountain Table, Shannon County, South Dakota.

Feet	Description
	Upper Zone
85	Gray silty ash. Horizontal bedding. Weathers in vertical walls and columns. Overlain by basal Arikaree white ash (Rosebud of Matthew).
	Middle Zone
111	Buff and gray-colored clays. *Protoceras* channel sandstone at several levels in upper 40 feet but not within 10 feet of upper gray ash. Sandstones highly fossiliferous. Clays moderately fossiliferous.
	Lower Zone
13	Light gray color with narrow brown band above and below (Light weathering band of Wanless).
90	Gray clays with brown hue. Least fossiliferous horizon of the Brule formation. Underlain by the upper nodular zone.

Few sections in the Big Badlands display this member so adequately. The upper gray ash beds and *Protoceras* channel sandstones are especially well developed and exposed. The *Leptauchenia* nodules, which constitute an important feature of the middle member in many sections, are absent but may be found a mile to the north on the west wall of the Table.

This member may be subdivided into three units. The lower zone includes approximately 100 feet of rather barren clays, capped with a light gray clay band as recognized by Wanless. The middle zone is that section where *Leptauchenia* nodules are developed and, in most instances, where channel sandstones are found. The upper unit is composed of vertically weathered silty ash. The contrasting lithology and weathering characteristics

of each unit make it usually possible for anyone to establish his position even though he may be unable to locate the exact boundary for the unit.

Lithologic units within a formation present rather broad chapters of the history of that formation. These afford a means by which paleontological evidence may be more accurately recorded. Thus, of prime importance are reliable boundary markers within the formation. The members and subdivisions of the Brule formation of the Big Badlands of South Dakota, as here designated and defined, fulfil these requirements.

References

Darton, N. H., 1899, Preliminary report on the geology and water resources of Nebraska west of the one hundred and third meridian: U. S. Geol. Survey 19th Ann. Rept., pt. 4, p. 719-785.

Hayden, F. V., 1857, Notes on the geology of the Mauvaises Terres of White River, Nebraska: Acad. Nat. Sci. Philadelphia Proc., v. 9, p. 151-158.

————, 1867, Report of F. V. Hayden, United States Geologist: U. S. Geol. Survey Terr. 1st Ann. Rept.

Matthew, W. D., 1907, A lower Miocene fauna from South Dakota: Am. Mus. Nat. History Bull., v. 23, p. 169-220.

Schultz, C. B., and Stout, T. M., 1938, Preliminary remarks on the Oligocene of Nebraska (abs.): Geol. Soc. America Bull., v. 49, p. 1921.

Wanless, H. R., 1923, The stratigraphy of the White River beds of South Dakota: Am. Philos. Soc. Proc., v. 62, p. 190-269.

Wood, H. E., 2d, et al., 1941, Nomenclature and correlation of the North American continental Tertiary: Geol. Soc. America Bull., v. 52, p. 1-48.

Wortman, J. L., 1893, On the divisions of the White River or lower Miocene of Dakota: Am. Mus. Nat. History Bull., v. 5, p. 95-105.

Museum of Geology
South Dakota School of Mines and Technology
Rapid City, South Dakota

[American Journal of Science, Vol. 254, July 1956, P. 433-451]

THE MAGNETIC PROPERTIES AND DIFFERENTIATION OF DOLERITE SILLS—A CRITICAL DISCUSSION

FREDERICK WALKER

ABSTRACT. The work of J. C. Jaeger and G. Joplin on the magnetic properties of the Great Lake dolerite sill Tasmania is discussed. The evidence available in similar intrusions elsewhere fails to confirm Jaeger and Joplin's conclusion that differentiation by crystal settling cannot take place because the sinking crystals remelt in zones of hotter magma. Nor was support found for their hypothesis that the differentiation of dolerite sills is accomplished by the settling of blocks of crystal mush which have become detached from the upper crystalline phase. Further tests of their hypotheses are, however, desirable.

INTRODUCTION

A recent paper by Professor J. C. Jaeger and Dr. G. Joplin of Canberra University on the magnetic properties of a Tasmanian dolerite sill is of great interest to petrologists, for their conclusions cut right across current views on the crystallization differentiation of basic sheets. A critical discussion is therefore desirable, and the present contribution forms a first step in this direction.

Their study (Jaeger and Joplin, 1955) deals with a bore-core 1050 feet long in a Trias-Jura dolerite sill at Great Lake. The collar is near the bottom of the upper chilled phase about 50 feet below the upper contact, and the estimated thickness of the sill is 1700-2000 feet. Thus the lower third at least, besides the greater part of the upper chilled phase, remains unexplored. Six other shorter cores were however available, one from the same sill and five from a nearby sill complex. Of these, two (including the other Great Lake core) traverse lower contacts, and one traverses both contacts of a 20 foot sill.

Previous work by P. M. S. Blackett on samples from the main Great Lake core having shown reversed magnetization in a few cases, Jaeger and Joplin's more complete investigation was undertaken in order to explore the possibility of errors being introduced during the handling of the core. Three hundred cylinders 7/16 inch long and 7/8 inch in diameter cut from the 1050-feet core at intervals of 5 feet or less were used, the magnetic intensity and susceptibility being measured for every specimen. The magnetization was assumed to be thermo-remanent, that is "to be acquired by the magnetic materials in the rock when they cool through their Curie points in the Earth's magnetic field, the direction of their magnetization being that of the Earth's field at that time." The specific gravity of each sample was also determined.

Jaeger and Joplin's measurements confirmed and amplified the work of Blackett and the results are summarized below:

(1) The intensity of magnetization shows low and increasing values in the region 0-50 feet below the surface but uniform values in the region 800-1500 feet with two or three isolated peaks.

(2) The region 50-800 feet shows a rise in the general level of intensity with an increase in the number and intensity of the peaks.

(3) The dip of magnetization is near 90° in all cases.

(4) Certain specimens show reversed magnetization, and though this is probably due in some cases to mismarking of the core, it was found that the

region above 700 feet is normally magnetized while that below 800 feet is reversed.

(5) The magnitude of the intensity varied from 0.24-4.05 c.g.s./cc x 10^3.

(6) The measurements of susceptibility show the same general characters as those of intensity.

(7) The density near the surface is 2.921, the mean density 0-1050 feet is 2.894, and the mean density 800-1050 feet is 2.964.

Jaeger and Joplin's results are not questioned in any way, and the following discussion is confined to the conclusions which they have drawn from them. The author's qualifications for embarking on such a discussion are an acquaintance with the contemporaneous and very similar intrusives of the Karroo and Palisadan dolerite provinces; the kind gift by Professor S. W. Carey of a series of buttons from the 1050-foot core, 180 of which have been sliced and petrographically examined; and lastly the privilege of friendly and stimulating personal discussion with Professor Jaeger.

GENERAL

The conclusions drawn by Jaeger and Joplin from their results fall into two groups. Those of the first are drawn directly from the magnetic measurements supplemented by petrographical examination and a few partial chemical analyses. The second group is developed from the first with the aid of calculations as to the rates of cooling, crystal settling, and remelting of settling crystals in dolerite sills. They are of prime importance to petrologists for they throw doubt on well established notions concerning the nature and mechanism of crystallization differentiation.

REMELTING OF SINKING CRYSTALS

Probably the most fundamental of Jaeger and Joplin's conclusions is that concerning the remelting of settling crystals. According to their calculations a crystal of 2 mm diameter will be unlikely to live more than a minute in a magma at a temperature above the melting point of the crystal. Assuming the absence of convection currents, they estimate that "a large crystal will not fall more than 1 cm. in a minute and in this time it would be remelted in hotter magma."

The author does not question the accuracy of Jaeger and Joplin's calculations and admits that, if conditions are as they are pictured, the possibility of significant differentiation by the settling of discrete crystals must be ruled out, in which case current ideas on crystallization differentiation are demolished by a single stroke. He considers, however, that there is a fatal objection to the remelting hypothesis which renders it untenable: *there is not and cannot be any hotter magma in which the settling crystals could remelt.* Take for example the Tasmanian dolerite sills. Microphenocrysts of pyroxene are found in the chilled basaltic contacts (Edwards, 1942, p. 464), showing that this constituent had begun to crystallize before emplacement. The magma must therefore have been supersaturated with pyroxene even before intrusion and supercooled below the freezing point of pyroxene, otherwise this mineral would not have started to crystallize. Since it is reasonable to suppose that the magma temperature fell continuously up to and beyond the time of em-

placement, it seems impossible that a settling pyroxene crystal would pass through magma above the temperature of a point on the liquidus boundary appropriate to its composition. Reaction might take place with the production of another phase, either continuously or discontinuously, but not plain remelting.

The author has examined the chilled contacts of several hundred dolerite intrusions from South Africa, America, and the British Isles, and in every case phenocrysts or microphenocrysts of the mafic minerals (i.e. those likely to settle) were found, showing that they had started to crystallize before intrusion, that the magma was supersaturated with respect to them, and that they could therefore settle without remelting, though they would react with the magma when not in equilibrium with it.

SETTLING OF BLOCKS FROM THE UPPER CHILLED PHASE

Although discrete crystals seem to have played the main part in the gravitational differentiation of dolerite sills, other processes such as roof stoping may have been operative. As pointed out by Jaeger and Joplin, Edwards (1942, p. 469) has called attention to this possibility, and the author has suggested that it may account for the diversity of types found in the coarser portions of quartz dolerite sills in mid-Scotland (Walker, 1952, p. 401). Neither Edwards nor the author gave details of mechanism, which remains problematical, but Jaeger and Joplin have developed a most interesting suggestion which serves as a useful basis for discussion.

JAEGER AND JOPLIN'S MUSH-SETTLING HYPOTHESIS

Jaeger and Joplin consider that roof stoping took place not by the separation of blocks from the upper crystallization phase but by the breaking away of the denser portions of a crystal mush immediately below it, consisting of interlaced crystals and residual liquid. Such a mush is considered by them to be formed by the downward movement of the level of solidification becoming greater than the settling rate of small crystals of magnesian pyroxene and calcic plagioclase. "Crystals falling from above will be impeded by new crystals formed below them, also the heavier crystals move downwards displacing lighter liquid upwards: thus, near the margin, conditions are favourable for the formation of a mush of crystals and residual liquid whose density increases downwards and in its lower parts is greater than that of the original magma. The tensile strength of such a mush of crystals and residual liquid would be small so that the lower and heavier part would break away and fall as a single entity to the bottom of the sill, leaving the lighter part behind. On this mechanism a maximum density should be attained near the base of the sill where the first blocks to fall meet the margin which has crystallized from the lower contact; the density should then decrease upwards, slowing at first and then more rapidly to a minimum near the roof of the sill. Also some magma may be expected to be trapped between blocks fallen from the roof and to have a composition appropriate to its own level: in the lower part of the sill this would correspond to slightly differentiated magma, and in the upper part to late differentiates.

"This mechanism was suggested by the magnetic results which seemed to indicate the existence of fairly homogeneous blocks separated by narrow regions with very different properties, and all the measurements discussed earlier agree with what might be expected on this hypothesis. The fit with density is excellent. The petrography of the lower portion is very uniform and consistent with slow cooling, while the abnormal regions in it correspond to less differentiated magma—for example, both the density and magnetic properties of the region 940-950 ft. are very similar to those at the top of the sill which were assumed to correspond to undifferentiated magma. The petrography of the upper portion corresponds to later differentiated material and segregation veins. The behaviour of total iron in the chemical analysis also fits in well" (p. 16-17).

Here then, is a detailed argument for discussion point by point.

(1) *Is the stoping of solid blocks from the upper crystalline phase more probable than the separation of a crystal mush below it?* This is very doubtful. It can be demonstrated in the case of many dolerite sills that the magma can stope blocks from the country rock of both contacts, and it seems quite likely that the same process may take place with the upper and lower crystalline phases once they have begun to develop contraction joints. Possibly magmatic movement is required for stoping to operate. Jaeger and Joplin's mush-settling hypothesis presents difficulties which are discussed below.

(2) *Is Jaeger and Joplin's mechanism for the development of a crystal mush a probable one?* The author's answer would be "no." As soon as the crystals of the mush come in contact a framework is set up which may have low tensile strength but should be capable of withstanding the downward pressure of settling crystals in a somewhat viscous magma. Prior to the formation of such a framework it is probable that some, at least, of the larger and earlier pyroxenes would push aside the smaller crystals obstructing their downward path, thus leaving the mush and settling individually. The settling of calcic plagioclase as postulated by Jaeger and Joplin would be very slow and probably negligible (Walker, 1940, p. 1088).

(3) *If the differentiation was accomplished by the settling of a spongy crystal framework in the manner suggested, should this be evident in the field, or in bore cores, or microscopically?* Almost certainly "yes." To produce a gravitational pull capable of disrupting even the weakest crystal framework there would have to be a high concentration of pyroxene in the lower and denser parts of the mush. The settled portions reaching the bottom of the magma chamber would therefore be so much more mafic than the narrow zones of surrounding magma that they should be easily detectable on any large exposure, or even in a split core specimen. Such differences of mineral composition should be even more obvious in a large thin section. Furthermore, if the heavy portion of the mush breaks away, the fracture might very well be above the mafic concentration, and the resulting mineralogical gradation should certainly be capable of detection. Detailed optical work should bring out differences of fabric and optical properties between the settled blocks and the interstitial rock.

(4) *Is there convincing evidence of the settling of stoped blocks or of portions of mafic crystal mush in the Great Lake bore core?* No. The magnetic variations recorded are of such a nature that they might equally well be expected in sills where settling of discrete crystals seems the only process competent to produce the observed differentiation. Such sills contain numerous schlieren of varying texture and mineralogy. A 7/8 inch core gives an extremely restricted view of the variation, especially when it fails to penetrate the lower two-fifths of the sill. In the Palisades sill (Walker, 1940, table 3) accumulative types are confined to the lowest fifth of the intrusion, and in the Mount Wellington sill (Edwards, 1942, table 4) to the lowest quarter. The critical evidence would therefore seem to be missing in the case of the Great Lake Sill, and examination of fresh artificial exposures of the lower portions is clearly desirable.

(5) *Are comparisons with dolerite sills from the Karroo and Palisadan provinces and with other Tasmanian sills valid, and if so, what conclusions may be drawn from the evidence shown by them?* Such comparisons are probably quite valid, for all three tholeiitic provinces have close chemical resemblances. Figure 1 shows this clearly, also the similarity in the differentiation trend of the Palisades and Mount Wellington sills. Tables 1 and 2 emphasize the slight petrological and chemical differences between as well as the

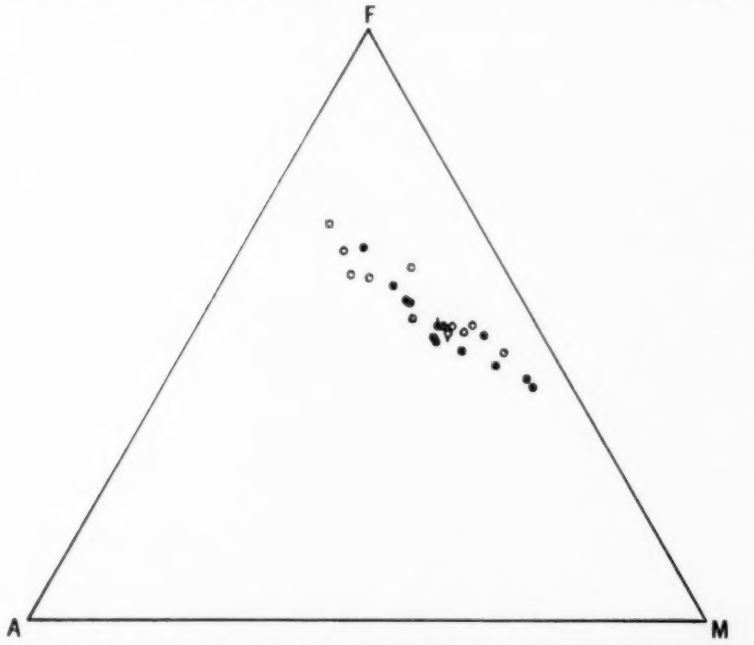


Fig. 1. Triangular plot of $Na_2O + K_2O$(A), FeO + Fe_2O_3(F), and MgO(M) for Palisade sill—filled circle, and Mount Wellington sill—open circle. Composition of basaltic contacts—circle marked by vertical line.

TABLE 1

	1	2	3
TiO_2	0.6	1.0	1.3
Fe_2O_3	0.5 } 8.8	1.2 } 10.5	1.6 } 10.3
FeO	8.3 }	9.3 }	8.7 }
CaO	11.5	10.3	10.0
Na_2O	1.6	2.1	2.4
$\frac{Na_2O \times 100}{Na_2O + CaO}$	12.2	16.9	19.4
Normative plagioclase %	48.5	47.8	49.0
Normative pyroxene %	39.1	40.8	39.3

(1) Average undifferentiated Tasmanian dolerite. Edwards (1942, table 3, 1).
(2) Average undifferentiated Karroo dolerite. Walker and Poldervaart (1949, table 17, 4).
(3) Average undifferentiated Palisade diabase. Walker and Poldervaart (1949, table 17, 10).

TABLE 2

	1	2	3
Thickness (feet)	1200	400	1000
Maximum % pyroxene (weight)	50	48	48
Minimum "	21	30	25
Maximum % plagioclase (weight)	54	52	53
Minimum "	38	40	29
Maximum % olivine (weight)	nil	19	23
Height of maximum colour index above lower contact (feet)	275	160	60

Mineral percentages of 1 are normative and of 2 and 3 micrometric.
(1) Mount Wellington sill. Data for calculation from Edwards (1942).
(2) Jagersfontein dolerite sill, Orange Free State. Data for calculation from Truswell (1955, fig. 1).
(3) Palisade sill. Walker (1940, table 3).

resemblances, table 1 dealing with the averages for the three provinces and table 2 with characteristic differentiated sills from each. Furthermore, the three provinces are almost contemporaneous and have much the same tectonic and sedimentary environments. The poverty of the intrusive phase in Tasmania is the only significant difference.

Mineralogically the Karroo and Palisadan sills are a little richer in olivine than the Tasmanian, so that some of them show a marked concentration of this mineral above the lower chilled phase in spite of the fact that the initial magma was normatively saturated.

One of these concentrations—the well known olivine ledge of the Palisade diabase—provides clear evidence that differentiation was effected by settling of individual crystals, rather than by blocks derived from the upper crystalline phase. The sill in question is approximately 1000 feet thick and shows a marked concentration of olivine 50 feet above the lower contact. The olivine-rich layer is 20 feet thick and contains 20-25 percent of olivine, as opposed to 2 percent in the basaltic contacts.

The top of the olivine layer is even, and the layer shows a rapid but continuous gradation into types much poorer in olivine, both above and below. This is taken as evidence that the crystallization and settling of olivine ceased abruptly at a relatively early stage when the sinking olivine crystals were unimpeded by crystals of other minerals (Walker, 1940, p. 1083-1089).

It is this smoothness of the top of the olivine layer that provides critical evidence. If the concentration of olivine was brought about by the accumulation of sinking olivine-rich blocks on the upward crystalline phase at the bottom of the sill, the top of the heap would be irregular, not smooth. Furthermore, the olivine layer is remarkably uniform in mineral composition, both laterally and vertically. The rare veins traversing the layer pass into normal rock above and below.

All this is quite inconsistent with an hypothesis of heaped blocks surrounded by interstitial magma of different and presumably olivine-poor composition. If sunken blocks do exist, they should certainly be detected on the unrivaled natural and artificial exposures of the Palisades. They would, for instance, be probably of smaller grain size than the interspace rock and would certainly be olivine-poor if not olivine-free. Actually, the grain size of the olivine layer is notably coarser than that of the adjacent dolerite (Walker, 1940, fig. 6).

The same arguments apply to pyroxene settling in the Palisade sill. But here the settling continued to a late stage, the crystallization range of pyroxene being much longer, and was only halted by crystal interference. (Some petrologists, including the author, have suggested increasing viscosity of the magma as a halting factor, but this is doubtful. The later fractions are richer in water than the earlier and produce rocks of coarser grain, which certainly does not indicate an increase in viscosity.) The proportion of pyroxene in the sill increases gradually downwards from below the upper chilled phase until a maximum is reached about 80 feet above the lower contact, that is, 10 feet above the olivine layer in the type section. The grain of the rock and the specific gravity vary sympathetically with the downward increase in pyroxene.

If the pyroxene concentration was caused by mafic and spongy blocks breaking away from the upper crystalline phase, there should surely be some evidence of them in the abundant fresh exposures visible in the lower portions of the sill, but none was recorded. Indeed, the uniform nature of the rock (apart from the olivine layer) at these lower levels is striking and is relieved only by a few later aplite or pegmatitic injections of roughly vertical disposition, or by very occasional horizontal bands of later but undifferentiated dolerite of finer grain. The material surrounding settled blocks would, on the contrary, have no regular shape or preferred orientation.

The differentiation process in the Mount Wellington sill seems to have been similar to that in the Palisades, but olivine played no part, for in this province it is confined to a few microphenocrysts sheathed with orthopyroxene in the basaltic contacts (Edwards, 1942, p. 580). The two 400-foot members of the multiple Karroo dolerite at Jagersfontein show a type of differentiation still nearer that of the Palisades, for in each member there is a marked concentration of olivine as well as pyroxene at lower levels. The mafic concentra-

tion is relatively higher than in the Palisade sill and this is probably due to later injections of undifferentiated magma above the lower contacts. Traces of such injections have in fact been detected (Truswell, 1955).

In the quartz-dolerite sills of Central Scotland (Walker, 1952) an irregular, patchy variation of mineralogy and texture in the coarser portions is much more consistent with an hypothesis of sinking blocks than anything the author has observed in the Palisadan province, or anything that has been described in the Tasmanian sills.

In questions of gravitational differentiation the possibility of convectional sorting must be considered. Remelting of sinking pyroxene crystals on a scale sufficient to produce convectional overturn in the magma may be ruled out, but the occurrence of layering, which is presumably convectional, is an observed fact in some dolerite sills.

The thickness of the Palisade sill (1000 feet) was probably insufficient for sorting by convection currents to be effective, for no layering is visible in the admirable natural exposures. But in the southward extension of the intrusion to the Delaware River, the thickness increases to 1600 feet, and layering begins to show itself. The unpublished micrometric work of F. H. Jacobeen (A. B. thesis, Princeton University) brings this out clearly and has been confirmed by the author. In the field the layering is not particularly conspicuous, but in the central portions thin bands of anorthosite alternate with others which are slightly more mafic than the average.

Comparable layering has not yet been detected in any of the Karroo or Tasmanian sills, but in the former case the investigated sheets are thinner and lacking in fresh artificial exposures. In the latter there are certain indications of abnormal viscosity during the later stages of consolidation, for devitrified glass takes the place of the micropegmatite found in the South African and Palisadan examples. Relative poverty in volatiles would, however, yield the same result.

If normal convectional layering is found in any sill, the settling and sorting of individual crystals may be taken as proven, though this does not rule out the sinking of blocks from the upper crystalline phase. But processes other than convection may produce a very similar type of layering. For instance, in the composite crinanite boss of Cnoc Rhaonastil, Islay, Inner Hebrides, the author and E. M. Patterson have found vertical veins up to 1 foot wide in which the pyroxene and plagioclase of the crinanite are segregated into vertical bands. Horizontal layering with preferred orientation of the plagioclase laths in the same azimuth is a more certain indication of convection but has seldom been recorded from dolerite sills.

CHEMICAL AND OPTICAL DATA

Neither the chemical nor the optical data given by Jaeger and Joplin provide adequate backing for their hypothesis of differentiation. This is due primarily to the inescapable fact that the Great Lake core fails to penetrate to levels where accumulative types might be expected to occur. Even so, something might have been gained by inclusion and correlation of quantitative optical and modal data. For instance, the modal proportion of iron ore would

be better suited for comparison with the magnetic properties than the normative magnetite and ilmenite. Jaeger and Joplin do indeed recognize that the hematite which is found to occur affects the magnetism, but no account is taken of Fe_2O_3 in the pyroxene structure. The analyses of Edwards (1942, table 10) show that this may be important. Furthermore, optical data on the pyroxene series—in particular, refractive index measurements—would have been helpful in determining whether these minerals belonged to an earlier or later position in the differentiation trend.

Jaeger and Joplin find difficulty in choosing suitable criteria for the classification of the coarser bands as dolerite-pegmatites or not, and the author feels that the fault may be his. In a recent contribution on this subject (Walker, 1953) he states that dolerite-pegmatites "possess the coarse grain and graphic intergrowth which are the two main features of the pegmatites proper." Now many of the coarser bands in the Great Lake core would undoubtedly be classed by him as dolerite-pegmatites, though they contain neither micropegmatite nor graphic intergrowth of augite and plagioclase. Grain size then, markedly coarser than that of the normal host rock must be the chief criterion. When he wrote on the subject, he had no experience of the Great Lake pegmatitic types which carry devitrified glass or indeterminate mesostasis in place of micropegmatite. He would emphasize, further, that the ratio $\frac{Fe_2O_3 \times 100}{FeO + Fe_2O_3}$ used by Jaeger and Joplin as a criterion is much less satisfactory than the iron-magnesia ratio $\frac{(FeO + Fe_2O_3) \times 100}{MgO + FeO + Fe_2O_3}$ and that in any case the ratios given by him in his earlier contribution (Walker, 1953, fig. 1) are only meant as a rough guide to be used in a relative sense in comparisons between dolerite-pegmatite and host rock.

GENERAL STATEMENT AND CONCLUSIONS

The foregoing discussion may perhaps, seem overcritical, but the author feels that by tempering his criticism in any way he would be doing a disservice to the most interesting and stimulating hypotheses of Jaeger and Joplin, to whom all igneous petrologists should be indebted. The author is particularly grateful to Professor Jaeger for his cordial cooperation and to Professor Carey for the very complete collection of buttons from the main core.

As things stand, Jaeger and Joplin's hypotheses have not yet been adequately tested. It has been shown already that their theory of the rapid remelting of small discrete crystals settling into zones of hotter magma is invalid in cases where the crystallization of the settling minerals had already commenced before emplacement. In such cases the magma is supersaturated with them and no superheat is available for their remelting. In every case examined by the author, crystallization of the constituents likely to settle *had* commenced before emplacement, but it is of course possible that Jaeger and Joplin's hypothesis is operative in certain special cases where magma ascends very rapidly from depth.

Jaeger and Joplin's mush-settling hypothesis requires very careful critical examination in the field and in the laboratory, for it might well take place along with the fall of discrete crystals. The limited evidence available is against it, in particular that provided by the excellently exposed Palisade sill, but the author considers that detailed examination of the best-exposed portions of the thick Tasmanian sills is highly desirable, especially the lower portions to which the Great Lake bore hole did not penetrate. Critical evidence might well be provided by road-cuttings, quarries and shore sections.[1]

Such field investigations should be backed up by laboratory studies. In the Tasmanian sills the chemical analyses of Edwards (1942) leave nothing to be desired, but there is a total lack of micrometric analyses and of refractive index determinations of the pyroxenes.

Quantitative spectrographic work, on the pyroxenes in particular, might well prove helpful, for by determining the distribution of the trace elements in the atomic structure, clues would be given as to the position of a mineral in the differentiation series. Quantitative mineragraphic work on the ores is also needed.

Reverting finally to the initial purpose of Jaeger and Joplin's paper, the determination of the magnetic properties of serial specimens from the main core, the author is ill qualified to offer any critical discussion. He considers, however, that the magnetic data fit the current theories of crystallization differentiation of basic sills, e.g. the Palisade diabase, quite as well as the novel hypotheses advanced by Jaeger and Joplin. Any thick dolerite sill which he has examined shows numerous pegmatitic schlieren in its upper portions which are rich in iron ore and would produce magnetic peaks comparable to those recorded in the Great Lake sill. At the lower levels these peaks become fewer, but the test of Jaeger and Joplin's hypothesis lies at still greater depths, as yet undrilled.

The hypothesis of gravitational differentiation by the settling of the early-formed mafic minerals has recently received a useful shakeout by Drever (1952) and Jaeger and Joplin's contribution provides another.

Recent work on basic sills shows that the problem is complicated much more than had been thought, by multiple intrusion, in particular, by bands and veins of virtually undifferentiated magma. If a hypothesis of block-settling of two-phase convection could be established for the Tasmanian or any other province, it would be of the greatest importance to petrogenic theory.

References

Drever, H. L., 1952, The origin of some ultramafic rocks: a preliminary survey of the evidence for and against the gravitative accumulation of olivine: (Revised abstract of a lecture to the Mineralogical Club of Copenhagen).

Edwards, A. B., 1942, Differentiation of the dolerites of Tasmania: Jour. Geology, v. 50, p. 451-480, 579-610.

Jaeger, J. C., and Joplin, Germaine, 1955, Rock magnetism and the differentiation of dolerite sills: Geol. Soc. Australia Jour., v. 2, p. 1-19.

[1] The author understands that a comprehensive collection from the Mount Wellington sill has already been made by Professor Jaeger.

Truswell, J. F., 1955, A petrological study of a dolerite sill in the Jagersfontein diamond mine, Orange Free State: Royal Soc. South Africa Trans., v. 34, p. 409-416.

Walker, Frederick, 1940, The differentiation of the Palisade diabase, New Jersey: Geol. Soc. America Bull., v. 51, p. 1059-1105.

————, 1952, Differentiation in a quartz-dolerite sill at Northfield quarry, Stirlingshire: Edinburgh Geol. Soc. Trans., v. 15, p. 393-405.

————, 1953, The pegmatitic differentiates of basic sheets: Am. Jour. Sci., v. 251, p. 41-60.

Walker, Frederick, and Poldervaart, Arie, 1949, Karroo dolerites of the Union of South Africa: Geol. Soc. America Bull., v. 60, p. 591-706.

University of Cape Town
South Africa

DISCUSSION

J. C. JAEGER and GERMAINE JOPLIN

Professor Walker raises a question of considerable importance which was not referred to in our paper. A priori it might be expected that in some intrusions the magma would be at a temperature above the liquidus point appropriate to its composition, while in others it might be below it. If its temperature were well below the liquidus point this should be apparent from the petrology, and we did not consider this case, tacitly confining our attention to that of a completely liquid magma. Walker, however, considers the intermediate case, that of a slightly supercooled magma, and asserts that the whole of the several hundred dolerite intrusions which he has examined do, in fact, belong to this category.

He bases this conclusion on the fact that in all cases microphenocrysts[1] (which he assumes to be intratelluric in origin) of the more mafic minerals are found in the chilled contacts. This observation does not constitute a complete proof, since it is possible that in the process of intrusion the outer portions of the sill lost a certain amount of heat and became supercooled while the magma was still in motion, leaving the inner portion still at a temperature above the liquidus. In this case phenocrysts would appear in the margins, but, by the arguments of Jaeger and Joplin (1955), single crystals could not settle through the sill.

We would prefer to take the view that there are three possibilities: (1) that the magma is initially at a temperature above its liquidus point in some region—in this case Walker agrees that the settling of single crystals through this region is impossible; (2) that the magma is supercooled or at a temperature slightly below its liquidus point throughout its volume—in this case crystals could settle through a sill, and in fact the existence of well defined layering attributable to crystal settling should be a better criterion for such a temperature of intrusion than the appearance of phenocrysts in the margins; (3) that the magma is intruded at a temperature well below its liquidus point

[1] In the Tasmanian dolerites microphenocrysts do appear in the margins but they are not abundant.

—in this case many and large phenocrysts would be present on intrusion and the petrography would be different again.

If sills are intruded under the conditions postulated by Walker, certain physical consequences follow which must be reflected in the petrology. They must initially be very uniform in composition and temperature (as remarked above, they cannot be much hotter in the center) and they must contain intratelluric phenocrysts throughout their volume in a proportion comparable with that at the margins. These phenocrysts will fall through the sill, possibly growing while they fall, and must arrive in the region near the surface of solidification which is moving upwards from the lower margin (though in this region they may possibly react with the liquid). Since the position of the surface of solidification can be estimated in order of magnitude with some certainty, this allows conclusions to be drawn about the viscosity of the magma.

The Palisades sill discussed by Walker (1940) appears to be of this type and will be considered as an example. Taking his figures, just after intrusion it consisted of 1000 feet of magma at a temperature of about 1100°C. containing 2 percent of phenocrysts of olivine of average diameter 0.25 mm. Assuming that heat is lost from the magma by conduction only, the time necessary for solidification to be complete at any distance from the contact can be calculated. Table 1 shows the time in years required for solidification to be complete at various distances from the margin calculated on the following assumptions (units are c.g.s., calorie, and °C.): initial temperature 1100°C.; solidification complete at 900°C.; specific heat of magma 0.3; specific heat of solid rock 0.24; density of magma and country rock 2.8; thermal conductivity of magma and rock 0.005; heat of solidification 100 cal/gm. liberated uniformly over the range 900-100°C.; initial temperature of country rock 0°C.

TABLE 1

	Distance from margin (ft.)					
	10	20	30	50	70	100
Time (years)	1.1	4.4	9.8	27	53	109

These results were calculated by the method of Carslaw and Jaeger (1947, ¶ 31); as remarked in Jaeger and Joplin they will not be altered by a factor of more than two or three by changing the numerical values assumed above to other likely values.

Thus it can be concluded that the time necessary for the level of solidification to proceed beyond the olivine layer (50 to 70 ft.) is of the order of some tens of years, and during this time the change in temperature of the center of the sill will be absolutely negligible (< 0.01°C).

The rate of fall of phenocrysts through the sill is determined by Stokes' law, the main uncertainty in the calculation being the viscosity of the magma. Bowen (1915) and subsequently Butler (1937), using a value of the order of 4 poises for the viscosity (derived from observations of liquid melts and an incorrect determination from the movement of Hawaiian lava), deduced

that a crystal would fall through the sill in a time of the order of a few weeks. Such low values of the viscosity are improbable but they cannot entirely be ruled out: if they should be the fact, the whole of the intratelluric phenocrysts would become concentrated within a few feet of the margin. Nichols (1939) has obtained values of the order of 4×10^4 poises from observations of Hawaiian lavas and quotes values of the same order for dry melts of basalt at 1150°C. (this value decreases very rapidly with increasing temperature). With these values, the time of fall of an olivine crystal 0.25 mm in diameter through the sill would be of the order of 1500 years.

If it is assumed that the olivine layer is derived from the microphenocrysts present when the sill was intruded, the previous calculations show that the last of these fell through 930 ft. in about 53 years. Taking (following Walker, 1940) 0.73 for the difference in density between olivine and liquid, and 0.11 mm for the diameter of the crystals in the upper part of the olivine layer, Stokes' law gives a value of 280 poises for the viscosity of the magma. The fact that this value is lower than those given above for dry melts is reasonable in view of the fact that the viscosity of magmas is assumed to be decreased by the presence of volatiles.

This assumption that the olivine phenocrysts present on intrusion are the source of the olivine layer agrees with observation in many ways. It gives a sharp top for the layer (except for the straggling due to variation in crystal size), and also a decrease in the average diameter of the crystals and an increase in their amount towards the top of the layer, although it does not account for its well defined lower surface.

What happens after all the phenocrysts initially present have fallen out remains to be considered. The authors have argued that the early-formed crystals near the upper margin will be trapped and will not fall out (this happens also to some intratelluric phenocrysts since these are found near the upper contact). There will thus be an hiatus between the end of the fall-out of intratelluric phenocrysts and the possible beginning of a "rain" of crystals from the upper region of solidification. Since the rate of advance of this region downwards is slow and much the same as that of the lower surface of solidification upwards, this rain should lead to a small uniform increase in density rather than to pronounced layering.

Finally it should be remarked that if Walker's statement that in all cases dolerite magmas are intruded at a temperature a little below the liquidus point corresponding to their composition is true in general there must be some reason for this physically rather surprising fact. Possibly this is connected with the rapid rise in viscosity at temperatures near the liquidus point (cf. figures by Kani quoted by Nichols (1939)) which might result in hotter magma always appearing as an extrusive.

We are now making a more detailed study of the Tasmanian sills in connection with which we shall discuss Walker's criticism of our "mush-settling" hypothesis elsewhere.

References

Bowen, N. L., 1915, Crystallization-differentiation in silicate liquids: Am. Jour. Sci., 4th ser., v. 39, p. 175-191.

Butler, J. W., Jr., 1937, On the time required to form the olivine zone in the Palisades sill, New Jersey (abs.): Am. Mineralogist, v. 22, p. 218-219.

Carslaw, H. S., and Jaeger, J. C., 1947, Conduction of heat in solids: Oxford, Oxford University Press.

Jaeger, J. C., and Joplin, Germaine, 1955, Rock magnetism and the differentiation of dolerite sills: Geol. Soc. Australia Jour., v. 2, p. 1-19.

Nichols, R. L., 1939, Viscosity of lava: Jour. Geology, v. 47, 290-302.

Walker, Frederick, 1940, The differentiation of the Palisade diabase, New Jersey: Geol. Soc. America Bull., v. 51, p. 1059-1105.

AUSTRALIAN NATIONAL UNIVERSITY
CANBERRA

DISCUSSION

H. H. HESS

At the request of the Editor, John Rodgers, I have read the interesting discussion of Jaeger's and Joplin's paper by Walker and the former authors' rejoinder. Friendly debate on petrological problems is rare and might well be profitable. At the risk of being the Devil's advocate I shall enter the ring and cast some doubts on the conclusions of one or both of the contending parties.

THE QUESTION OF SUPERHEAT

On theoretical grounds I am inclined to support Jaeger and Joplin in their opinion that basaltic magmas, such as represented by the Palisades, Karroo and Tasmanian dolerite sills, may be emplaced with an appreciable amount of superheat. Dolerites begin to crystallize at a temperature slightly above 1100°C. To generate a dolerite magma one must go to a depth of at least 100 km in the Earth judging from recent estimates of the geothermal gradient. The melting point of diopside increases about 3° per kilometer depth. Augite may be expected to behave similarly. Thus by analogy at 100 km the temperature of melting for the basalt would be above 1400°C. Allowing for some adiabatic cooling, a magma generated at 100 km one might expect would arrive at shallow depth with a considerable amount of superheat. The above is essentially the reasoning of Daly as expressed many years ago.

The evidence cited by Walker against superheat consists of the common occurrence of pyroxene microphenocrysts in the chilled border facies of dolerite sills as Bowen has also contended. However, those in the border facies of the Palisades sill with which I am familiar are rounded and show every indication of being resorbed by the magma at the time the magma was quenched along the contact.[1] If these had been phenocrysts in the magma, at the site of generation of the magma, some 100 km below the surface, they would certainly not have reached shallow depth without melting if one accepts Jaeger's and Joplin's reasoning. Assuming the maximum possible velocity in transit, at least ten hours must be involved, but Jaeger and Joplin give the life of a crystal of 0.1 cm as not more than a minute in magma above the liquidus. I disagree with the last-cited authors on this point for reasons given below. I would conclude from the petrographic evidence that the magma had

[1] Most of the augites are present as glomeroporphyritic aggregates suggestive of relicts of small gabbroic xenoliths.

a temperature at least above the solidus for augite in a basaltic liquid because it was in the process of dissolving the augite microphenocrysts at the time of quenching. On the other hand, Sosman and Merwin (1913) found that the arkose fragments included in the Palisades dolerite could be half fused at 1150°C., but petrographic examination of the inclusions showed that they had not flowed. This puts a limit on possible superheat at less than 50°C.

It appears that a large part but possibly not all of the superheat was lost in transit. Several means may be suggested by which it could be lost: (1) very slow transfer of the magma from depth; (2) rapid transfer from depth to a relatively shallow reservoir, a pause and reintrusion upward; (3) dissolving of phenocrysts or xenocrysts which were much more abundant at the initial site of magma than they were when it reached shallow depth. One can only approach a judgment on the probability of any or all of these alternatives inductively. For large fissure eruptions or sills of great lateral extent a rapid, one-stage transfer of the liquid from its site of generation to the surface or the level at which it reaches hydrostatic equilibrium seems probable on purely mechanical grounds. The writer sampled the lower chilled border facies of the Palisades-Rocky Hill sill along a perimeter of 100 km. This is the same order of magnitude as the distance the magma presumably traveled vertically. No changes in chemical composition were found beyond expected analytical error nor were there noticeable differences with respect to proportion or condition of the small augite phenocrysts. This strongly suggests high velocity of intrusion, "high" in the sense that there was not enough time for reaction with wall rocks or further resorption or crystallization of microphenocrysts. One can fairly assume by analogy a high vertical velocity in transfer of the magma from depth. The above proposed mechanisms seem rather inadequate to get rid of the amount of the superheat postulated. This leaves a problem to be solved. One may conclude that superheat may be present, but to an extent less than 50°C.

"MELTING" OF CRYSTALS

I disagree completely with Jaeger's and Joplin's reasoning whereby a crystal of 0.1 cm will disappear by "melting" in a fraction of a second to less than a minute in magma above its crystallization temperature. For the purposes of this discussion the melting temperature of the pyroxene is taken as that temperature at which it melts if the crystals are heated in contact with an inert environment such as is done experimentally in a laboratory furnace. For augite this might be 200°C. above the liquidus temperature of the magma. The fact that the interior of the crystal reaches the liquidus temperature of the basalt by heat conduction in a matter of seconds has little bearing on the problem at hand. Crystals in magma above the liquidus react with and are *dissolved* by the magma. How fast this process will take place involves a number of factors which are too poorly known to calculate a rate. It might be supposed that resorption of the augite by the magma would result in a film of liquid around the crystal which would be saturated in the constituents of the pyroxene. Further resorption would be dependent on diffusion of ions into and out of this film. This might slow down the process to a matter of hours or days rather than seconds or minutes.

TABLE 1

Settling Velocities of Crystals in Meters per Year

	Plagioclase				Pyroxene				Chromite				
	0.1				0.7				1.4				Density crystals less density magma
Viscosity in Poises ↓	0.5	1.0	1.5	2.0	0.1	0.5	1.0	2.0	0.1	0.25	0.5	1.0	Radius in mm
300	57	229	515	916	16	400	1602	6408	32	200	801	3204	
1000	17	69	153	274	4.8	120	481	1922	9.6	60	240	961	
3000	5.7	23	52	92	1.6	40	160	641	3.2	20	80	320	Preferred values
10000	1.7	6.9	15	27	.48	12	48	192	.96	6	24	96	
30000	.57	2.3	5.2	9.2	.16	4	16	64	.32	2	8	32	

For magma density 2.58

SETTLING OF CRYSTALS AND OTHER THINGS

The physical mechanisms which Jaeger and Joplin suggest for differentiation of the Tasmanian dolerite sill under discussion are extraordinarily interesting and probably applicable to some cases of differentiation, but I agree completely with Walker that they are quite inapplicable to dolerite sills for the reasons he states.

Let us consider the quantitative aspects relating to settling which Jaeger and Joplin did very nicely. In table 1 I have carried out the necessary arithmetic to show the relations between settling rates, viscosities, densities, and sizes of crystals. This is instructive because it shows at a glance that settling rates vary directly with density difference, inversely with viscosity increase but as the *square* of the radius of the settling objects. It is interesting to note that 1-mm radius plagioclase crystals settle slightly faster than .25-mm radius chromites.

The slow rate of settling of 1-mm crystals is amply illustrated in the table and in Jaeger's and Joplin's figures. But let us consider the case of magma which contains 1 percent of pyroxene crystals. Its density will be .006 gm/cc greater than magma without crystals. Let us arbitrarily take a sphere of such magma 1 meter in radius. It would have a settling velocity approximately 10,000 times that of the 1-mm radius pyroxene crystal. Even without any crystallization the slight density difference resulting from cooling would produce magma with a relatively high settling velocity. The conclusion to be drawn from this is that convective circulation is almost inevitable and probably plays a large role in the mechanism of differentiation.

Jaeger and Joplin propose differentiation by crystallization below the roof contact and either stoping of solid blocks or settling of a crystal mush with some residual liquid. They prefer the latter hypothesis. Walker points out the absence of evidence in the lower portions of dolerite sills to substantiate either of these hypotheses though such evidence ought to be observable. The second hypothesis modified to make the "mush" a rather dilute suspension of crystals in magma, coupled with convection, is essentially the mechanism proposed by Wager and Deer for the Skaergaard Intrusion and the one I would favor for the Stillwater Complex. The characteristic feature of these intrusions, the Bushveld, Great Dyke, Sierra Leone norite and others, is the development of igneous lamination. It is produced because settling crystals will tend to accumulate with their longer axes parallel to the floor upon which sedimentation of crystals is occurring. It is an inevitable result of crystal settling provided that the crystals are not equidimensional. Igneous lamination is virtually unkown in dolerite sills, and therefore I would conclude that the differentiation process does not involve crystal settling to an appreciable extent.

The considered conclusion of petrologists over the past 50 years has been that crystal settling was the mechanism of differentiation in the Palisades sill (Lewis, Bowen, Walker, Bailey, Fenner, Daly, and Barth). To disagree with such a galaxy is perhaps injudicious, but the evidence seems to me to point toward some other process. I would agree that the *large* olivine crystals of the olivine layer (the olivines are in two distinct generations) probably did

settle from the overlying liquid, and to this quantitatively small extent the above writers are correct.

The major process as I see it is a simple one, merely crystallization inward from surfaces of cooling. Let us look at the situation from the floor upwards. From 15 to 30 feet of magma were chilled against the floor and crystallized completely with a composition close to that of the original liquid. Above this crystals began to form along the solid-liquid contact. These would be the earliest crystals to separate from such a magma. The liquid immediately in contact with these crystals would be changed in composition by separation of the crystals. If it were left in contact with them until all of it had crystallized, the resulting rock would of course have the same composition as the original liquid. If, however, it is being continually removed by convection, then another layer of early crystals may form upon the first, thus shielding them from further reaction. This process continued will produce exactly the same crystals as would have been produced by crystallization above and settling to the floor, but the igneous lamination which should result from settling will be absent (as it is). If this process operated with 100 percent efficiency one would expect a more drastic differentiation than is actually observed. Presumably the sweeping away of the liquid is not complete, some is always trapped among the crystals, and to this extent the differentiation becomes less extreme.

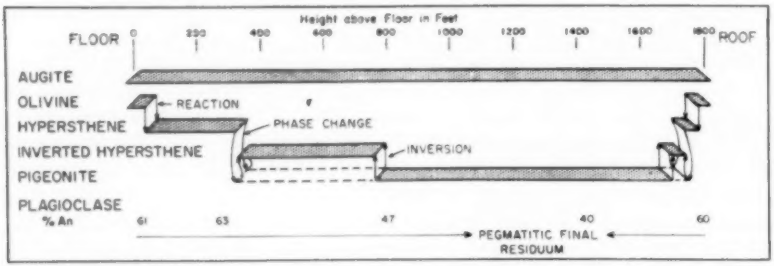


Fig. 1. Crystallization sequence in the Lambertville sill after F. H. Jacobeen, Jr. (1949).

One might expect from this process a similar differentiation from the roof downward and such is also the case. Jacobeen (unpublished bachelor's thesis) studied the Lambertville sill along the Delaware River and reproduced as figure 1 is his diagrammatic presentation of the mineralogical changes in the sill from floor to roof. It may be noted that the amount of crystallization from the roof downward is about a quarter of that from the floor upward. This is to be expected in a convecting liquid where the hotter portion tends to rise to the roof and cooler portions spread out on the floor. The concentration of micropegmatite and iron oxides in the last residual liquid thus normally occurs about 3/4 of the way from floor to roof.

COMMENT ON REMANENT MAGNETISM

Jaeger and Joplin consider magnetic measurements to "form an extremely sensitive tool" for study of differentiation of dolerite sills. To this I

take mild exception because rock magnetism is a gross property, much as is density, and not very significant unless broken down into its constituent parts. I think it is an extremely interesting property to study for is own sake, and on this score I would like to compliment the above authors for their work on the Tasmanian sill.

Rock magnetism is a very complex property related not to the total iron oxide content of a rock but only to the metallic oxide phases of Fe and Ti present, to thermal history and other relationships (Buddington and Balsley, 1954). Most urgently needed to go along with Jaeger's and Joplin's interesting paper is a study of the ore minerals in each of their samples.

References

Balsley, J. R., and Buddington, A. F., 1954, Correlation of reverse magnetism and negative anomalies with certain minerals: Jour. Geomagnetism and Geoelectricity, v. 6, p. 176-181.

Sosman, R. B., and Merwin, H. E., 1913, Date on the intrusion temperature of the Palisades diabase: Washington Acad. Sci. Jour., v. 3, p. 389-395.

Princeton University
Princeton, N. J.

REVIEWS

Reflections of a Physicist, 2d ed.; by P. W. Bridgman. P. xiv, 576. New York, 1955 (Philosophical Library, $6.00).—Bridgman here offers a collection of thirty-two philosophical articles and speeches which date back to 1929 and cover a range of subjects from epistomology to national security. To the first edition, he has added ten papers which comprise his philosophical writings since 1949. There are no articles appearing here for the first time.

The plan of this publication makes a certain amount of repetition inevitable and hampers the reader who attempts to focus on Bridgman's philosophical position. This task is further complicated by the change of meaning and emphasis which Bridgman acknowledges, but for which he never properly compensates. There is, for example, ambiguity among the ideas which continually draw Bridgman's attention and seem to be basic in his thinking. Simple fact is said to be venerable and supreme, and excites the scientist to scientific activity. However, the object of scientific activity is not to capture simple fact but rather to understand. It is furthermore a well known point of Bridgman's philosophy that useful concepts must be given an operational meaning. Precisely how ostensive fact, understanding, useful concept, and operational meaning are interrelated is a matter never given a comprehensive review. Bridgman is apparently not interested in formulating a careful epistomology but rather hopes to propagate a few of the important lessons learned by physicists in the revolution of physical thought which followed Einstein.

It is in this role that Bridgman is perhaps most interesting. Despite his professed differences with "most physicists," he represents a popular front of opinion on two counts: (a) his desire to find and exalt that which can be trusted to survive all possible renovations of physical thought; and (b) his pragmatic judgments with respect to many philosophical problems. If *Reflections of a Physicist* is a compendium of Bridgman's thinking, it is also an index to ideas which have become prominent among many scientific workers —sociologists and psychologists as well as physicists.

In addition to being of interest with respect to a popular scientific movement, *Reflections of a Physicist* offers an opportunity to study Bridgman's operational meanings. Many philosophers of science have recognized the legitimate methodological role of "operations" and have assigned them a place in scientific epistomology. The reviewer believes that a critical reading of Bridgman's work will serve to fix the strength and limitations of these operational meanings and will help the reader to determine the appropriateness of Professor Bridgman's philosophical contribution. In this connection, attention is drawn to a symposium on Operationalism held in December of 1953 under the chairmanship of H. Margenau, and reported in Scientific Monthly, v. 79 (October, 1954). At this meeting, Bridgman's views are discussed and criticized by six leading philosophers of science, most of whom recognize a certain validity in the operational point of view but prefer a more modest appraisal of its worth.

R. MOULD

Structural Geology for Petroleum Geologists; by William L. Russell. P. x, 427; 149 figs., 7 tables. New York, 1955 (McGraw-Hill Book Company, $7.50).—The publishers of this textbook state that "the author has eliminated

all topics that, though usually included under Structural Geology, have no actual relation to oil work, such as igneous and metamorphic rocks." Russell has not gone as far off the deep end toward teaching only one phase of structural geology as the publishers might imply, but the book does have a format distinctly different from that of other structural geology textbooks.

One-quarter of the book deals with the traditional structures—folds, faults, joints, unconformities. These chapters are clearly written, and the definitions and descriptions are generally conventional. Some readers may find points on which they disagree with the author, but probably none of them will be of major importance. In general his choice of terminology in disputed areas has been good. For example, Russell's classification of faults uses *normal* and *reverse* for high-angle faults, and *thrust* for low-angle faults; it does not mix genetic terms in with descriptive terms.

Russell has used illustrations from petroleum geology wherever possible, and at the end of each discussion he emphasizes the practical uses of the concept. In view of the fact (as Russell points out) that most students who graduate in geology now go into the petroleum industry or work closely allied to it, this may seem to some like a long overdue improvement in structural geology textbooks. Actually, it is probably just a big step forward in the direction of an already established trend.

Not as much of the classical approach to structural geology has been omitted from the text as might at first be thought; much of the non-petroliferous discussion is present, but it is found in unobtrusive descriptions rather than in blazing headlines. However, significant material, such as discussion of plutonic and metamorphic structures, has been eliminated. The book contains no discussion of volcanic or pyroclastic rocks or structures, and yet some geologists are finding that pyroclastic material is much more abundant in oil-type stratigraphy than is generally recognized. This attempt at a purely technical "bread and butter" training, in lieu of striving for a good foundation of scientific knowledge, does not seem to be in harmony with the present trend of the petroleum industry to increase its basic research into all phases of geology—even igneous and metamorphic geology. In the space gained by the deletions, Russell has added much-needed discussions of map interpretation, the practical uses of structural geology in the search for oil, and the classification of oil traps. Some of the additions, such as brief notes on sedimentation, compaction, permeability, regional geology, and effects of type of deposition on oil potential are more completely discussed in textbooks on other phases of geology. This space might have been more profitably used for a brief, non-comprehensive discussion of plutonic, metamorphic, and volcanic structures—thus making this a complete text on structural geology designed for petroleum geologists.

The student interested in further research will find a selected and up-to-date bibliography included on every important subject—far from complete, but sufficient to lead to the major papers.

Some, possibly many, teachers may not wish to use *Structural Geology for Petroleum Geologists* as a textbook because of the omission of certain phases of structural geology. Teachers who accept Dr. Russell's philosophy

of directed training will not only find this new format to their liking but will find it a technical book that is written in a simple, clear, generally non-technical style that makes for easy reading. Practicing petroleum geologists will find it a handy reference. DONALD H. KUPFER

New Zealand Geomorphology; by C. A. COTTON. P. 281; 115 figs., 16 pls. Wellington, 1955 (New Zealand University Press, 42 shillings).—This is a republication of sixteen articles that appeared between 1912 and 1925 in various scientific journals. The book is therefore analogous to W. M. Davis' well-known *Geographical Essays*, except that all the papers deal with a variety of aspects of the morphology of New Zealand.

Professor Cotton has long been an adherent of Davis' method of systematic description of land forms, a method reflected in Cotton's widely known textbooks. It is nowhere better exemplified than in this group of articles, really essays, which will be welcomed for their lucid descriptions and their clear illustrations. RICHARD FOSTER FLINT

Beyond the Hundredth Meridian—John Wesley Powell and the Second Opening of the West; by WALLACE STEGNER. P. 438; 12 figs., 7 maps. Boston, 1954 (Houghton Mifflin Company, $6.00).—There are essentially two stories in this biography of Powell—the first being the account of how a rather thinly educated Illinois schoolteacher began to make collecting trips in the West and through his native brilliance, hard work, and overwhelming tenacity ended up as the director of the Powell surveys, which were sponsored by the United States Government. Young Powell was a naturalist whose wide interests later centered on geology and the ethnology of the American Indian. Between 1867 and about 1880, when he succeeded Clarence King as director of the U. S. Geological Survey, Powell traveled, studied, and directed the studies of others in the Colorado Plateaus and parts of the adjacent Rocky Mountains.

From these studies came lengthy geologic reports and maps, some entirely the work of Powell and others prepared by Dutton and Gilbert under Powell's supervision. From one of these papers the concept of baselevel was formulated. W. M. Davis recognized from Powell's and Gilbert's descriptions the importance of subaerial erosion over marine erosion and built on Powell's data his concepts of the "geographical cycle." Davis likewise found Powell's descriptions of buried erosion surfaces suggestive of the logical end product of the cycle of erosion of the peneplain. Powell's explanation of why the Green River flows across the end of the Uinta Mountains came to be accepted as the basis for the concept of the antecedent stream. Had he acomplished nothing more, Powell would still be remembered for his recognition of key geologic facts and for the significant ideas he planted in the written reports of his travels.

In writing of Powell's life Professor Stegner does not accent these geological contributions, but so carefully has he chronicled Powell's field work and critically described his writings that the reader can almost see great principles of geology taking form in a man's mind and appearing on the printed page.

Probably the high points of Powell's life were his two boat trips of discovery and exploration down the Colorado River through the Grand Canyon. While these were scientific trips for the purposes of collecting data and mapping, they are, as Stegner describes them, tales of true adventure of strong, courageous men in conflict with nature. As Stegner has himself made the trip down the Colorado, he is eminently qualified to write about Powell's.

The second story that Stegner tells in this Powell biography deals with the conflicts of the War Department, Congress, and private individuals over the financing, regulation, and purposes of scientific exploration of the West. These problems were partially resolved by the creation of the U. S. Geological Survey. Although the dynamic Clarence King was chosen as its first head, Powell was singularly dominant in its formation and after two years succeeded King as director. During his long years with the Survey, Powell set up policies regarding mapping, publishing of reports, etc., as well as insisting that there should be civilian control of these activities. Powell's contributions and ideas regarding grazing, mineral rights, irrigation, etc., on the semi-arid government lands of the West (i.e., west of the "100th meridian," which is generally accepted as the dividing line between normal and dry land agriculture) brought into the open scientific problems which seemed then to be settled on the basis of practical politics and economic pressures. Mr. Stegner reminds us that the 20th century dilemma of conflicts between politically trained congressmen and government officials—both groups interested in vote-getting policies—and scientists interested primarily in research and factual deductions is no new thing on the American scene. Perhaps the most lasting lesson to be learned from the life of John Wesley Powell is that scientifically trained people must always be aware of the social implications of their work and, like Powell, fight hard for what they believe is right without merely fighting to build up or re-enforce their own little competitive empire.

Stegner has done an excellent job in the documentation of Powell's life and has included contemporary paintings and photography. Especially striking are several sepia reproductions of Holmes' pen and ink sketches of the Grand Canyon area taken from Dutton's *Tertiary History of the Grand Canyon District*.

SHERWOOD D. TUTTLE
HARRY H. CROSBY

Publications Recently Received

Bibliography of the Literature on the Minor Elements and Their Relation to Plant and Animal Nutrition, 4th ed., v. 4. New York, 1955 (Chilean Nitrate Educational Bureau, Inc., 120 Broadway).

Atlas of Paleogeographic Maps of North America: by Charles Schuchert. New York, 1955 (John Wiley & Sons, $4.75).

The North American Midwest, A Regional Geography: J. H. Garland, editor. New York, 1955 (John Wiley & Sons, $8.00).

Man and the Winds: by E. Aubert de la Rue. New York, 1955 (Philosophical Library, $6.00).

New Zealand Geomorphology: by C. A. Cotton. Wellington, 1955 (New Zealand University Press, 42 *s*).

An Introduction to Botany, 3d ed.: by A. W. Haupt. New York, 1955 (McGraw-Hill Book Company, $5.50).

La Théorie du Champ Unifié d'Einstein; by M.-A. Tonnelat. Paris, 1955 (Gauthier-Villars, 2500 francs).

University of California Publications in Geological Sciences: V. 31, no. 4, Classification of Clypeasteroid Echinoids; by J. W. Durham ($2.00). V. 32, no. 1, Volcanism in the Southern Part of El Salvador; by Howel Williams and Helmut Meyer-Abich ($1.00). Berkeley and Los Angeles, 1955.

Nuclear Magnetic Resonance; by E. R. Andrew. New York, 1956 (Cambridge University Press, $6.50).

Science and Modern Life; by Sir. E. J. Russell. New York, 1955 (Philosophical Library, $2.75).

Fossil Plants of the Carboniferous Rocks of Great Britain (2d section); by Robert Crookall. Geol. Survey Great Britain Memoirs, Palaeontology, v. 4, pt. 1. London, 1955 (Her Majesty's Stationery Office, £3 0 *s* 0 *d*).

On the Nature of Man; by D. D. Runes. New York, 1956 (Philosophical Library, $3.00).

Soil Physics, 3d ed.; by L. D. Baver. New York, 1956 (John Wiley & Sons, $7.75).

Pleistocene Studies in the Malaprabha Basin; by R. V. Joshi. Deccan College Research Institute Pub. 1. Poona, 1955 (Rs. 15/-).

Die Forschung am Menschen. Erster teil, Einschliesslich Rassenkunde und Rassengeschichte der Menschheit; by E. F. von Eickstedt. Stuttgart, 1955 (Ferdinand Enke Verlag, DM 28.-).

Scientific American Books: The New Astronomy. The Physics and Chemistry of Life. First Book of Animals. Atomic Power. Automatic Control. Each compiled by the Editors of Scientific American. New York, 1956 (Simon and Schuster, $1.00 each).

U. S. Geological Survey Water-Supply Papers: 1199, Quality of Surface Waters of the United States, 1951, Pts. 7-8, Lower Mississippi River Basin and Western Gulf of Mexico Basins ($1.75). 1200, Pts. 9-14, Colorado River Basin to Pacific Slope Basins in Oregon and Lower Columbia River Basin ($2.00). 1267, Water Levels and Artesian Pressures in Observation Wells in the United States 1953, Pt. 3, North-Central States ($1.00). 1274, Surface Water Supply of the United States 1953, Pt. 2-B, South Atlantic Slope and Eastern Gulf of Mexico Basins, Ogeechee to Pearly River ($1.25). 1276, Pt. 3-B, Cumberland and Tennessee River Basins ($1.00). 1284, Pt. 10, The Great Basin ($1.00). 1285, Pt. 11, Pacific Slope Basins in California, ($1.75). 1316, Compilation of Records of Surface Waters of the United States through September 1950, Pt. 12, Pacific Slope Basins in Washington and Upper Columbia River Basin. ($2.25). 1327, Ground-water Resources of the Prairie Creek Unit of the Lower Platte River Basin, Nebraska; by R. T. Sniegocki ($2.00). 1330-A, Water Requirements of the Pulp and Paper Industry; by O. D. Mussey ($ .60). 1357, Computations of Total Sediment Discharge, Niograra River near Cody, Nebraska; by B. R. Colby and C. H. Hembree ($ .70). 1362, Quality of Surface Water for Irrigation, Western United States, 1952 ($ .75).

U. S. Geological Survey Professional Papers: 262, Pleistocene Geology of Eastern South Dakota; by R. F. Flint ($3.00). 268, The Central Kuskokwim Region, Alaska; by W. M. Cady, R. E. Wallace, J. M. Hoare, and E. J. Webber ($3.75). 274-B, Characteristic Jurassic Mollusks from Northern Alaska; by R. W. Imlay ($ .25).

Praktische Edelstein-Prüfung; by B. W. Anderson. Stuttgart, 1955 (Rühle-Diebener-Verlag, DM 24.90).

Reports of the Swedish Deep-sea Expedition, 1947-1948; edited by Hans Pettersson. Vol. 2, Fasc. 2, Zoology (Kr. 15); Vol. 4, Fasc. 1, Bottom Investigations (Kr. 25); Vol. 6, Fasc. 1, Sediment Cores from the West Pacific (Kr. 10); Vol. 7, Fasc. 2, Sediment Cores from the North Atlantic Ocean (Kr. 5); Vol. 7, Fasc. 3, Sediment Cores from the North Atlantic Ocean (Kr. 8); Vol. 10, Fasc. 1, Special Investigations (Kr. 8). Gothenburg, 1954-1955 (Elanders Boktryckeri Aktiebolag).

Modern Surveying for Civil Engineers, 2d ed. revised; by H. F. Birchal. New York, 1956 (Philosophical Library, $15.00).

California Div. Mines Special Reports: 43, Geology of a Portion of the Elsinore Fault Zone, California; by J. F. Mann ($ .75). 44, Bibliography of Marine Geology and Oceanography, California Coast; by R. D. Terry ($ .75). San Francisco, 1955.

Fuel, Solid, Liquid and Gaseous, 5th ed.; by J. S. S. Brame and J. G. King. New York and London, 1955 (St.Martin's Press and Edward Arnold, Ltd., $10.00).

Panorama of Progress. Jour. of The Franklin Institute, v. 261, no. 1. Philadelphia, 1956 ($1.00).

Steels for the User, 3d ed. revised; by R. T. Rolfe. New York, 1956 (Philosophical Library, $10.00).

VOL. 254 No. 7, 1956

American Journal of Science

JULY 1956

CONTENTS

The Metamorphic History of the Spruce Pine District
J. Laurence Kulp and Arie Poldervaart 393

Occurrence of Uranium in Seth-la-kai Diatreme, Hopi Buttes, Arizona
J. David Lowell 404

The Formation of Gore Mountain Garnet and Hornblende at High Temperature and Pressure ..... *Robert H. Wentorf, Jr.* 413

The Isotopic Variation of Common Lead in Galena from the Front Range and Its Geological Significance
George Phair and Henry Mela, Jr. 420

Geographic Names for Members of the Brule Formation of the Big Badlands of South Dakota ..... *James D. Bump* 429

DISCUSSION

The Magnetic Properties and Differentiation of Dolerite Sills—A Critical Discussion
Frederick Walker 433

Discussion ..... *J. C. Jaeger and Germaine Joplin* 443

Discussion ..... *H. H. Hess* 446

REVIEWS

Reflections of a Physicist, 2d ed.; by P. W. Bridgman ..... *R. Mould* 452

Structural Geology for Petroleum Geologists; by William L. Russell
Donald H. Kupfer 452

New Zealand Geomorphology; by C. A. Cotton ..... *Richard Foster Flint* 454

Beyond the Hundredth Meridian—John Wesley Powell and the Second Opening of the West; by Wallace Stegner ..... *Sherwood D. Tuttle*
Harry H. Crosby 454

Publications Recently Received 455